For Reference

NOT TO BE TAKEN FROM THIS ROOM

AN INVESTIGATION INTO THE STRENGTH REDUCING EFFECTS OF PLAIN SCARF JOINTS IN LAMINATED WOOD BEAMS

by

C. K. A. Stieda

DEPARTMENT OF CIVIL ENGINEERING

Ex libris
universitatis
albertaensis

Digitized by the Internet Archive
in 2017 with funding from
University of Alberta Libraries

https://archive.org/details/stieda1958

Thesis
1958
#28

THE UNIVERSITY OF ALBERTA

AN INVESTIGATION INTO THE STRENGTH REDUCING EFFECTS OF PLAIN SCARF JOINTS IN LAMINATED WOOD BEAMS

A DISSERTATION

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

FACULTY OF ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

BY

C. K. A. Stieda

EDMONTON, ALBERTA

April 3, 1958

SYNOPSIS

This thesis presents the results of an investigation into the strength of laminated wood beams containing one or more plain scarf joints with a scarf slope of 1:12.

In the first phase of the investigation two types of beams containing a single plain scarf joint were compared with unmatched control beams. It is shown that the strength of the scarf joint is not always the factor determining the flexural strength of the glulam beam. Spiral grain, simple tension or compression failures may terminate the load carrying ability before the scarf joint has failed. The unexpected occurrence of a large number of failures due to spiral grain has been of particular interest in these tests. The mean strength of beams failing at the scarf joint has been compared with that of the control beams. For unplaned beams a strength ratio of 0.82 has been computed, a value considerably smaller than proposed by the Canadian Standards Association. For specimens where the bottom lamination containing the scarf joint had been planed after assembly of the beam the mean initial failure stress was the same as that of the control beams.

The second phase of the investigation required a comparison of the strength of glulam beams containing a number of plain scarf joints spaced according to various patterns. No significant difference in strength for these various scarf joint spacings has been found.

Acknowledgements

The author of this thesis gladly acknowledges the large degree of assistance and help he received from various quarters, especially members of the staff of the University of Alberta.

Professor J. Longworth of the Department of Civil Engineering, who introduced the writer to the problems investigated, helped greatly with his guidance throughout the investigation. He read the whole manuscript and offered much valuable criticism, which was greatly appreciated.

The Canadian Institute of Timber Construction, which sponsored the investigation, gave valuable information. Western Archrib Structures of Edmonton provided the lumber for the test beams which were manufactured by Stein Roof Structures of Edmonton. The Forest Products Laboratory of Canada prepared a statistical analysis of the test results.

Valuable information on the structure of Douglas Fir and especially on spiral grain was given to the writer by Dr. R. G. H. Cormack of the Botany Department. Mr. J. Melnyk of the Plant Science Department kindly assisted in the preparation of photomicrographs.

Messrs. A. Widholm, H. Kupczynski, D. Williams and G. Vincent, students, and Mr. Heinz Panse, laboratory assistant, very ably assisted in the testing of the beams.

Mrs. A. Jellis typed the whole thesis with great enthusiasm.

I N D E X

	Page
Introduction	1
Object and Scope	8
Materials and Assembling of Beams	9
Experimental Procedure	11
Test Results	13
Discussion	67
Conclusions	92
Bibliography	94

Appendices:

A.	Forest Products Laboratory Report	97
B.	Statistical Analysis	101
C.	Glulam Certificates	105
D.	Effect of Sliding Friction at the Supports on the Computation of the Modulus of Elasticity	108
E.	Some Remarks on the Structure of Coniferous Wood	110

LIST OF TABLES

Table		Page
1	Efficiencies of Plain Scarf Joints	4
2A	Test Results, Series C, S and SP	13
2B	Test Results, Series CW, X, Y and Z	19
3A	Mean Initial Failure Stresses, Series C, S and SP	23
3B	Mean Ultimate Failure Stresses, Series C, S and SP	24
4A	Mean Initial Failure Stresses, Series CW, X, Y and Z	24
4B	Mean Ultimate Failure Stresses, Series CW, X, Y and Z	24
5A	Strength Ratios, Series C, S and SP	25
5B	Strength Ratios, Series CW, X, Y and Z	25
6A	Average Specific Gravity and Moisture Content, Series C, S and SP	26
6B	Average Specific Gravity and Moisture Content, Series CW, X, Y and Z	26
7A	Average of Moduli of Elasticity, Series C, S and SP	26
7B	Average of Moduli of Elasticity, Series CW, X, Y and Z	27
8	Specific Gravity Distribution of Lumber for Series X, Y and Z	68
9	Specific Gravity Distribution of Lumber for Series CW.	68

LIST OF DIAGRAMS

Figure		Page
1.	Misaligned Plain Scarf Joint	5
2.	Hooked Scarf Joint and Joint with End Steps.	5
3.	Specific Gravity Distribution of Top Samples, Beam Series C, S and SP.	28
4.	Specific Gravity Distribution of Bottom Samples, Beam Series C, S and SP.	28
5.	Specific Gravity Distribution of Lumber for Series X, Y and Z.	29
6.	Specific Gravity Distribution of Lumber for Series CW.	29
7.	Lay Up of Laminations According to Specific Gravity.	29
8.	Specific Gravity Distribution of Samples, Beam Series X, Y, Z and CW.	30
9.	Laminated Wood Beams, Series S and SP.	31
10.	Laminated Wood Beams, Series X.	32
11.	Laminated Wood Beams, Series Y.	33
12.	Laminated Wood Beams, Series Z.	34
13.	Types of Failure in Wood.	35
14.	Moisture Distribution in Beam S-12.	70
15.	Stress-Strain Curve for Wood and Theoretical Flexural Stress Distribution.	35
16.	Effect of Cross Grain on Failure at the Scarf Joint.	36

LIST OF DIAGRAMS

Figure		Page
17A.	Load Deflection Curves, Beam Series C, S and SP	37
17B.	Load Deflection Curves, Beam Series CW, X, Y and Z	46
18A.	Beams, Series C, S and SP	50
18B.	Beams, Series CW, X, Y and Z	59
19.	Typical Failures	63
20.	Cross Section of Douglas Fir	114
21.	Longitudinal Sections of Douglas Fir	115

INTRODUCTION

Glued Laminated Timber Construction is defined by the Canadian Standards Association (3)* as a"method for producing large elements by gluing together a number of (timber) laminations having their grain essentially parallel". The thickness of these laminations usually is 1 or 2 inch nominal. The structural material resulting from glued lamination is called GLULAM (3).

In order to make long spans possible it is necessary to end-join shorter timbers to form a continuous structural element. Since it is possible to stagger joints in adjacent laminations a continuous solid section can be produced. Up to the present, only few data have been collected on the actual performance of joints in glulam. Although glulam has been used widely in Europe for nearly 50 years (17) the German code for timber construction, DIN 1052 (4), only mentions the subject of strength of joints in laminated timber construction in a general way. The code only contains a recommendation that joints be placed at sections not fully stressed and that the slope of scarf joints be between 1:5 and 1:10. It also requires in members subject to bending that the section modulus of the section at the joint be at least that of the full member.

The first major attempt on this continent at applying engineering analysis to glulam was made by T.R.C. Wilson (10) of the U. S. Forest Products Laboratory in 1935. It was not until 1943 that the first preliminary design specifications for

* Numbers in parenthesis refer to references listed at the end of this paper.

glulam construction were issued in the United States. These design principles were contained in a design directive issued by the U. S. War Production Board. A year later this directive was adopted by the National Lumber Manufacturers Association and reissued as the "National Design Specification for Stress Grade Lumber" (13).

This specification, still in use today, mainly contains basic stress values for glulam construction. It gives little or no information with respect to location and effect of knots and end-joints of different kinds. The revised 1955 edition however contains an extensive list of references, which may be of value to the researcher. More information on the research done up to 1954 can be found in a publication "Fabrication and Design of Glued Laminated Wood Structural Members" by A. D. Freas and M. L. Selbo (9).

The results of investigations on the performance of glued joints were published for the first time by the U. S. Forest Products Laboratory in 1946 (11). This report gives performance data on plain scarf joints, fingered joints and Onsrud joints. Tension and compression strength parallel to the grain for glue-jointed specimens were compared with the strength of solid, continuous specimens.

The plain scarf joints varied greatly in tensile strength depending on the slope of the scarfs. Ratios of the tensile strength of plain-scarf jointed specimens of Douglas Fir to those containing no scarf joint ranged from 0.55 for a 1:3 scarf to 0.95 for a 1:20 scarf. Similar ratios were obtained for White Oak specimens. The report suggests that scarf joint efficiency of 100%

is not possible since in an end joint part of the cross-sectional area of the summerwood, which is of high strength, is joined to spring wood which is much lower in strength.

All other joints were found to be less efficient than plain scarf joints of a slope of 1:10 or flatter, (e.g of an efficiency less than 90%).

Data on the behaviour of various joints in beams were published in 1947 by the same laboratory (18). In this report 117 pairs of test beams with 8, 11 and 17 laminations free from significant defects and having end joints of various types in several locations were compared to matched beams with continuous laminations. These beams having a cross section of 5 in x 12 in, 14 ft. long, were loaded by two single loads and subjected to bending till rupture occurred. In order to prevent shear failure of the beams the two loads, spaced symmetrically to the centre of the beam, were applied as close to the centre as the spacing of joints would permit. From the results of these tests and those mentioned above (11) it was concluded that scarf joints with a slope not steeper than 1:5 can be permitted in laminations on the compression side of the neutral axis of a beam without detriment to its strength.

Laminated beams containing scarf joints of 1:5, 1:8 and 1:12 in the outer lamination on the tension side were found not to be seriously deficient in strength, when compared with those having continuous laminations. The data presented indicate that the strength of a beam having a jointed lamination on the tension side is controlled by the strength of that lamination, unless that

lamination is so weak that the load causing it to fail is insufficient to cause failure of the reduced beam formed by considering the failed outer lamination to be ineffective. The report recommends that the stress in a lamination be restricted at the joint to a specific fraction of the strength of a continuous lamination. Proposed strength ratios were based on the performance of joints in previous tension tests (Table 1) (11).

TABLE 1

Efficiencies of Plain Scarf Joints in Tension.

Slope of Scarf	Observed Efficiency On Matched Specimen	Recommended Efficiency
1:20	95%	90%
1:10	90 to 85%	85%
1:5	less than 70%	65%

The superiority of plain scarf joints over other joints as already demonstrated by the previous tension tests was verified by this beam test series.

The Canadian Standards Association adopted these strength ratios (Table 1) and they were incorporated into the CSA Specification for Glued-Laminated Timber Construction (3).

While plain scarf joints had been proven to be of high efficiency, some manufacturers found them difficult to assemble. Unless extreme care was exercised, there was always the possibility that one side of the scarf would override the other (Fig. 1). The resulting depression between the two laminations would cause a further decrease in the strength of the member. To avoid this difficulty and provide a speedier assembly and lining up of scarf

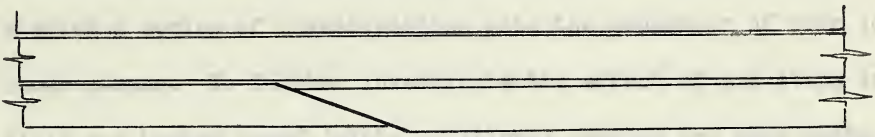
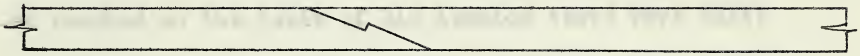


FIG. 1
MISALIGNED PLAIN SCARF JOINT
CAUSING DISCONTINUITY IN LAMINATION



HOOKED SCARF JOINT

SCARF JOINT WITH END STEPS
FIG. 2

FIG. 1
MISALIGNED PLAIN SCARF JOINT
CAUSING DISCONTINUITY IN LAMINATION

HOOKED SCARF JOINT

FIG. 2
SCARF JOINT WITH END STEPS

joints, some manufacturers produced a hooked scarf joint with or without end steps (Fig. 2). To determine the efficiency of such a joint the Canadian Institute of Timber Construction in 1953 started a series of investigations into the behaviour of such joints under stress. To further investigate the effect of end steps in plain and hooked scarf joints additional tension and beam tests were conducted under the direction of the Canadian Institute of Timber Construction during the years of 1954 - 56.

The results of these investigations were published in a thesis by Mr. Selwyn P. Fox in 1956 (8). Some of the conclusions he reached on the basis of his tension tests were that:

"Strength ratios of single scarf-jointed laminations (containing end steps and hooks) when tested in tension parallel to the grain are lower than those estimated by the provisions of the present C.S.A. specifications for glued laminated timber construction.

2. Strength ratios of single and double scarf-jointed laminations may be increased considerably by removal of the end-step notch on the outside faces of the laminations.

3. Tensile tests of notched, unjointed laminations have confirmed the trend of decrease in tensile strength with increase in notch depth of scarf jointed laminations."

To investigate in more detail the apparent increase in the strength ratio of scarf joints with end steps removed on the outside lamination, a further series of beam tests was conducted again under the auspices of the Canadian Institute of Timber

Construction at the University of Alberta during the winter of 1955/56. The results of this investigation have been presented in a thesis by Mr. R.C. Edlund (5). On the basis of his test results, Edlund concluded that removal of end-steps on the outside face of a scarf-jointed lamination in a glulam beam increases considerably the strength-ratio and the bending strength of such a beam. After the inefficiency of a scarf joint with end steps had been established, one of the remaining problems was to show how efficient a plain scarf joint was. Some work in this direction had already been done by the Forest Products Laboratory in the United States (18). However those findings had to be confirmed and if possible, expanded for the manufacturing conditions found in Canada. The Canadian Institute of Timber Construction therefore, in the fall of 1956 arranged a further program of beam tests at the University of Alberta. One series of tests was designed to obtain more information on the strength ratio for beams containing a single plain scarf joint in the bottom lamination. Another test series was designed to investigate the effect of certain scarf spacings. These investigations and their results are presented in this thesis.

OBJECT AND SCOPE

The object of the investigation presented in this thesis was twofold. Firstly, it was required to find the strength characteristics of certain plain scarf joints. Secondly, the effect of various spacings of plain scarf joints was sought.

Five groups of beams were tested. To find the effect of a single plain scarf joint on the modulus of rupture, two types of beams were tested.

Type (1) had a pre-glued joint in the bottom lamination in the region of maximum moment.

Type (2) was the same as (1) except that the bottom lamination containing the scarf joint was planed after the beam had been assembled. This was done to remove any possible uneveness at the scarf.

To find the effect of various spacings of plain scarf joints on the modulus of rupture the following three types of beams were tested:

(1) Beams containing scarf joints on top of each other at the centre in all laminations, e.g. zero spacing.

(2) Beams with joints in all laminations arranged as an inclined plane.

(3) Beams with joints in all laminations spaced a distance of twenty-four times the lamination thickness in adjacent laminations.

MATERIALS AND ASSEMBLING OF BEAMS

The working plan called for the manufacture and testing of 120 glulam beams. These beams were to be manufactured from 1-inch laminating lumber of clear, straight-grained, close-grained Douglas Fir from one car load or shipment.

Great care was taken to adhere to these specifications as far as feasible. However, the supplier of the material found it impossible to fulfil all the requirements for each piece. Even after about three quarter of the chosen carload had been rejected, the remaining material still contained some minor defects. Especially preponderant was the occurrence of cross grain. Since this is often difficult to detect by visual inspection (1) a considerable amount of cross-grained pieces went into the test beams. This was only discovered later when a fair number of beams failed due to cross grain.

Two loads of lumber were selected. As the first set of beams, manufactured from the first load of lumber, was tested it became obvious that the specific gravity of these beams varied widely (Fig. 3 and 4). In order to reduce the possible effect of such a variation in the specific gravity of the material, the second load of lumber was graded by the writer according to the specific gravity of the individual pieces. The beams were then laminated in such a way that the specific gravity of the individual laminations decreased from the outside towards the centre of the beam, except that the few boards showing an exceptionally large specific gravity were put in the very centre of the beams.

Lumber for the control beams of the second series was selected at a later date.

The beams were manufactured in two sets. The first set contained 25 unscarfed control beams, series C, 25 scarf-jointed beams, series S, and 25 scarf-jointed and dressed beams, series SP. End-joints located in the center of the bottom lamination were pre-glued plain scarf joints without end steps. Each beam consisted of seven laminations having a final cross section of about 2-3/8 x 5-1/4 in^2 (Fig. 9). This set of beams was manufactured from the first load of lumber.

The second set of beams was intended for a study of the effect of various scarf-joint spacings on the strength of beams. Manufactured were six beams of zero t spacing, e.g. joints one on top of each other at the center, series X, six beams with joints arranged as an inclined plane, series Y and six beams of 24 t spacing, e.g. scarf joints spaced 18 in. apart in adjacent laminations, series Z, seven control beams, series CW (Fig. 10 to 12). The scarfs were pre-glued and the laminations lightly dressed before assembly. Again each beam contained seven laminations. These beams were manufactured from the second load of lumber graded according to specific gravity. The laminations in the beams were placed in such a way as previously mentioned.

EXPERIMENTAL PROCEDURE

A modified screw type tensile testing machine was used to load the beams. This testing machine of 150000 lbs capacity, built by Riehle Brothers in East Moline, Illinois, had been modified by the addition of two horizontal steel beams for the purpose of bending tests. Two pedestals, placed at the required equal distance to either side of the centre of the load applying head of the testing machine, were fastened to the lower steel beam. To each one of these a steel plate was hinged, which supported the test beams. Point loading at the third points of the beam was applied through wooden blocks ($3\text{-}1/4 \times 3\text{-}1/4 \times 4$ in^3) which were acted on by triangular shaped steel pieces loaded directly by the upper steel beam. Load was applied continuously at a constant speed of 0.01 in/min. Deflection readings were taken at 1000 lbs intervals. For this purpose a scale graduated into 1/50 in increments was affixed to the beam at the center.. A fine string then was stretched from one end of the beam to the other. On one end this string was fixed to the beam, while at the other end it ran over a small nail in the beam and was held taught by a weight attached to the free end of the string. The string was fastened to the side of the beam at mid-height. As the beam deflected under load the string would remain in its original position and thus permit a direct reading of the deflection on the centre scale.

Moisture content and specific gravity of the beams were determined from small cubes, approximately $2\text{-}1/2 \times 2\text{-}1/2 \times 2\text{-}1/2$ in^3. These samples were cut from the beams immediately after testing.

In series C, S and SP samples for specific gravity were cut both from the top as well as from the bottom, while only the former were used for a moisture content determination. In series X, Y, Z and CW samples were cut from that face of the beam that failed first. Specific gravity of all beams has been defined as the ratio of dry weight in grams to volume in cubic centimeters of the sample. The volume here is that of the dry sample.

All beams were tested on a test span that provided a depth-to-length ratio of 1:24. For the beams of series C, S and SP this test span was 10.62 ft, while for the beams of series X, Y, Z and CW the corresponding span was 8.54 ft.

TABLE 2 A

LAMINATED WOOD BEAM TESTS - SERIES C

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1.FAILURE LOAD	(6) 2.FAILURE LOAD	(7) TYPE OF 1.FAIL.	(8) 2.FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
1	0.47	10.7	4.1	4 420		SP*		
2	0.58	14.1	4.2	5 100		SP		
3	0.50	16.5	2.4	3 960		T		Failure at knot hole under one load point.
4	0.58	13.7	2.7	4 330	5 360	Local T	SH	
5	0.57	15.7	3.2	4 350		CG		
6	0.53	13.1	1.9	2 930		CG 1:4		Cross grain across two laminations
7	0.51	9.9	3.2	4 320	4 830	C	T	40% glue fail. between 2 and 3 laminations.
8	0.56	15.0	2.1	3 520		SH CG		
9	0.47	10.3	2.5	3 330	4 000	T at knot	SP	
10	0.51	10.4	3.7	4 520		SP		
11	0.51	9.6	2.9	5 390	6 290	Local T at knot	SP	
12	0.49	11.9	4.1	5 730		CG 1:11		Slope of grain 1:22
13	0.52	12.9	3.2	5 000	5 240	C	SH	

* A list of the abbreviations is at the end of Table 2 B on page 22.

TABLE 2 A

LAMINATED WOOD BEAM TESTS - SERIES C, 14 - 25

(1) BEAM No.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1.FAILURE LOAD	(6) 2.FAILURE LOAD	(7) TYPE OF 1.FAIL.	(8) 2.FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
14	0.49	11.8	3.2	5 000	-	SH		Bottom not cracked.
15	0.60	10.4	3.2	5 290	-	SP		
16	0.63	11.4	3.0	4 350	-	CG		
17	0.57	13.8	2.8	4 000	-	CG		
18	0.55	17.3	3.7	4 960	-	SH		Bottom not cracked.
19	0.44	14.4	1.65	4 020T (2750T)	4340	Local T at point of gr. irreg.	SP	CG in 2. Lam.
20	0.55	16.5	2.3	(4 150)	4760	Local T	SP	
21	0.58	11.7	1.7	2 860	-	G + T		After taking off load this beam has been loaded again ASC-21A
21A	-	-	3.2	3 460	3 610	T	T	At a deflect of 4.55 beam was still "elastic", test discont.
22	0.66	13.6	1.9	3 320	4 250	T	SP	
23	0.67	10.0	2.9	3 620	4 340	Local T	SP	
24	0.62	10.8	2.7	4 540	-	SP		
25	0.48	13.0	3.0	3 660	4 230	T	SP	Partly reduced Sect. at 2. Fail.

TABLE 2 A

LAMINATED WOOD BEAM TESTS - SERIES 3, 1 - 13

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1. FAILURE LOAD	(6) 2. FAILURE LOAD	(7) TYPE 1, FAIL.	(8) OF 2. FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
1	0.56	10.6	1.5	2 170	2 850	SC + CG	CG 1:11	Slope of grain 1:11
2								
3	0.52	11.1	2.0	2 770	-	SC		Deep wood F.
4	0.51	9.5	3.8	4 830	3 940	CG	C	
5	0.64	11.0	1.2	2 400	3 710	CG	T	
6	0.56	11.1	1.2	2 010	-	SC + T		75% glue F. along scarf
7	0.66	13.1	3.3	6 300	-	SC		Deep wood
8	0.51	10.5	3.4	5 210	-	SP		
9	0.64	11.1	2.3	3 730	-	SF		
10	0.56	12.3	2.8	3 840	-	SH + CG		
11	0.57	12.0	1.9	3 650	3 770	T	T (Fail. cont.)	
12	0.47	9.6	2.2	4 040	4 760	CG 1:13	C	S.of G. 1:13 to 1:16
13	0.53	11.4	1.4	2 370	-	CG 1:6		

TABLE 2 A

LAMINATED WOOD BEAM TESTS - SERIES 3, 14 - 25

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1. FAILURE LOAD	(6) 2.FAILURE LOAD	(7) (8) TYPE OF 1. FAIL.	2.FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
14	0.49	8.7	1.6	2 280	3 130	CG 1:11	CG	3900 CG in top Lam. Slope of grain 1:11
15	0.65	8.6	1.3	2 410	-	TR at knot		
16	0.58	9.4	1.9	3 000	3 950	Local CG	CG 1:145	SL.G 1:11
17	0.51	9.4	1.8	2 770	3 480	CG	CG 1:9	SL.G.1:10
18	0.54	9.2	2.5	3 930	4 000	CG Top	CG Bottom	Starting at knot hole
19	0.52	9.8	1.9	3 510	-	CG + SC 1:7.5		10% glue F. + 70% deep wood F. SL.G. 1:11
20	0.52	10.2	2.0	3 000	3 480	Local T at hole CG		
21	0.63	10.4	2.7	4 690	-	CG + SC		20% shallow wood F.
22	0.52	11.3	1.8	3 060	3 890	SC	C	80% shallow wood F knot hole in upper part of scarf
23	0.46	11.1	2.4	3 290	-	SC + CG1:13		35% glue F. 15% wood F.
24	0.57	10.6	1.5	2 450	4 000	CG 1:13	CG +Sc	30 % glue F. 4030 T
25	0.55	12.1	2.2	3 740	-	CG 1:11		

TABLE 2 A

LAMINATED WOOD BEAM TESTS - SERIES - SP, 1 - 13

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1.FAILURE LOAD	(6) 2.FAILURE LOAD	(7) TYPE OF 1.FAIL.	(8) 2.FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
1	0.53	9.5	2.3	3 490	4 120	1.T CR	2. SC	Only edge splintered off at 1.
2	0.43	9.5	2.1	3 350	3 270	CG	SP	
3	0.52	9.8	2.6	4 000	4 070	T	CG	
4	0.52	9.5	1.8	2 880	4 210	CG	C	
5	0.43	11.3	2.7	4 620	-	SC		
6	0.54	8.6	3.1	3 990	4 390	CR	CG	Crack in bottom Lam.
7	0.53	9.6	2.6	4 590	5 310	CR	SP	
8	0.58	9.4	2.4	3 940	-	CG + SC		
9	0.57	9.1	2.3	3 700	4 440	CG	CG	Initial crack continued.
10	0.60	7.9	2.3	3 730	4 420		SC	
11	0.51	10.1	2.7	3 920	4 640	CR	CG	
12	0.58	10.7	1.7	3 000	-	CG	-	
13	0.46	10.6	1.5	2 690	-	CG + SC		

TABLE 2 A

LAMINATED WOOD BEAM TESTS SERIES SP, 14 - 25

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1. FAILURE LOAD	(6) 2. FAILURE LOAD	(7) TYPE OF 1. FAIL.	(8) 2. FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
14	0.50	11.8	2.0	3 340	4 710	CR	SC/CG + TR	
15	0.54	10.6	2.5	4 840	-	SC	-	
16	0.54	10.7	1.6	2 670	3 230	CG	CG	
17	0.60	10.7	2.5	3 930	-	CG	-	
18	0.49	14.0	2.2	3 300	4 160	CR	CG	
19	0.54	11.3	2.2	3 620	4 110	TR(K)	CG	Failure at knot (3) continued.
20	0.65	11.8	2.0	3 440	4 100	CR	CG (Sc)	5100 SP
21	0.47	10.8	2.8	4 360	4 010	SP (SC)	SP	
22	0.54	10.0	2.2	3 380	3 640	CG	CG	Extending only in short dist. l. Lam.
23.	0.59	10.7	1.6	2 860	3 680	(Local cracking at knot hole.)	CG	
24	0.50	10.5	2.1	3 080	3 340	CG	SC	
25	0.51	9.3	1.8	2 670	-	CG	-	

TABLE 2 B

LAMINATED WOOD BEAM TESTS - SERIES CW, 1 - 7

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1. FAIL. LOAD	(6) 2. FAIL. LOAD	(7) TYPE OF 1. FAIL.	(8) 2. FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			Material in outside Lams.
1	0.58	-	2.6	4 890	5 700	C	SP	A A
2	0.52	-	3.1	6 000	6 550	C	Local T and SH	B A
3	0.51	-	2.8	4 820	5 500	C	TR + SH	A A SH along growth surface in 2. Lam.
4	0.52	-	2.7	4 360	4 520	C	CG 1:13	B A
5	0.58	-	3.2	5 340	-	SP		A A
6	0.55	-	2.9	5 500	5 710	C	T	B A
	Average 0.543							
7	0.47	-	2.3	3 000	3 670	Local T	SP	E E

TABLE 2 B

LAMINATED WOOD BEAM TESTS - SERIES X, 1 - 6

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1.FAILURE LOAD	(6) 2.FAILURE LOAD	(7) TYPE OF 1.FAIL.	(8) TYPE OF 2.FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
1	0.63	12.8	2.6	4 820	-	T+CG		
2.	0.62	13.0	2.2	4 420	4 710	(Long) T (CR)	C- Through scarf, top.	
3.	0.60	13.5	2.1	4 000	4 640	C scarf, top.	SC - Shallow wood F.(T) 1+2 Lam.	
4.	0.59	13.0	1.7	4 000	4 580	C scarf, top	SC-65% Shallow wood F. (T)	
5.	0.58	12.7	2.5	4 440	4 730	C scarf, top	CG	
6.	0.59	12.9	1.6	3 000	4 500	Local CG	C through scarf	
	Average 0.602							

TABLE 2 B

LAMINATED WOOD BEAM TESTS - SERIES Y, 1 - 6

(1) BEAM NO.	(2) SPEC. GRAVITY	(3) MOISTURE CONTENT	(4) MAX. DEFLECTION	(5) 1.FAILURE LOAD	(6) 2.FAILURE LOAD	(7) TYPE OF 1.FAIL.	(8) 2.FAIL.	(9) REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
1.	0.60	9.6	2.9	5 210	-	SC		Along scarf of 2. Lam. Bottom Lam. unbroken
2.	0.57	11.2	1.7	3 260	5 620	T	SP	75% shallow wood F along scarf in bottom Lam.
3.	0.61	12.1	1.7	3 770	-	Partial CG 1:11		Crack Cont. along scarf SL.G 1:11
4.	0.60	12.5	2.25	4 470	-	CG + SP 1:8		F. along scarf SL.G 1:8
5.	0.57	14.5	2.45	4 100	4 520	C	SP + CG	Wood F. along scarf in 2 + 3 Lam.
6.	0.56	15.8	2.8	4 400	4 940	C	SP	Shallow wood F. along scarf of 2. Lam.
	Average .585							

TABLE 2 B.

LAMINATED WOOD BEAM TESTS - SERIES Z, 1 - 6

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
BEAM NO.	SPEC. GRAVITY	MOISTURE CONTENT	MAX. DEFLECTION	1.FAIL. LOAD	2.FAIL. LOAD	TYPE OF 1.FAIL.	TYPE OF 2.FAIL.	REMARKS
	gr/cm^3	%	in.	lbs.	lbs.			
1	0.57	12.6	2.4	4 740	4 750	C	CG 1:9	F. Cont. along scarf in 1 + 2 Lam. SL.G= 1:8
2	0.60	13.4	2.7	4 430	4 480	CG	SC	20% deep wood F.
3	0.57	12.8	2.8	4 850	-	T		Compr. F. just prior to 4 850.
4	0.55	14.3	2.6	5 400	5 090	C	SC	Deep wood F. along scarf of 1.+2. Lam.
5	0.56	12.5	2.4	4 840	5 070	Local T	SP	F. Cont. along scarf of 2. Lam.
6	0.61	12.6	2.2	4 590	-	CG 1:15		F. Cont. along scarf of 1.+2. Lam.
	Average 0.577							

ABBREVIATIONS

SC	at scarf	CR	one single crack, extending only partly through the 1 lamination
CG	cross grain failure	TR	transverse failure
T	tension failure	SH	shear
C	compression failure	G	glue line failure
SP	splintering tension	SLG	slope of grain

TABLE 3 A

Mean Initial Failure Stresses

Series C, S and SP

Failure Type		Beam Type		
		C*	S	SP
Tension	N	13	3	7
	$\bar{x}$,psi	8280	8200	7472
	S	1430	1710	952
	V	17.9	20.8	12.8
Cross Grain	N	5	11	9
	$\bar{x}$,psi	8330	6250	6368
	S	617	1615	876
	V	7.4	25.8	13.8
Compression	N	3		
	$\bar{x}$,psi	8550		
	S	1160		
	V	13.6		
Scarf	N		8	6
	$\bar{x}$,psi		6770	8290
	S		871	1545
	V		12.9	18.6
Group Mean exclusive compression	N	18	22	22
	$\bar{x}$,psi	8300	6710	7246
	S	1560	2120	1290
	V	18.8	31.6	17.8

* Two control beams failed in shear at an average horizontal shear stress of 400 psi.

TABLE 3 B

Mean Ultimate Failure Stresses - Series C, S and SP.

		C	S	SP
Group Mean	N	19	19	22
Exclusive Compression Failures	$\bar{x}$	8750	7160	7860
	S	1575	1950	1440
	V	18.0	27.2	18.3

TABLE 4 A

Mean Initial Failure Stresses - Series CW, X, Y and Z.

		CW*	X	Y	Z
Group Mean Including Compression Failures	N	6	6	6	6
	$\bar{x}$	11600	9300	9500	10850
	S	1310	1420	1500	748
	V	11.3	15.2	15.8	6.9

* The one specimen of low specific gravity had an initial failure stress of 6700 psi.

TABLE 4 B

Mean Ultimate Failure Stresses - Series CW, X, Y and Z.

		CW*	X	Y	Z
Group Mean Including Compression Failures	N	6	6	6	6
	$\bar{x}$	12500	10550	10750	10850
	S	1480	259	1460	569
	V	11.8	2.5	13.6	5.2

* The one specimen of low specific gravity had an ultimate failure stress of 8250 psi.

TABLE 5 A

Strength Ratios

SERIES C, S AND SP - BASED ON INITIAL FAILURE STRESSES

(a) Cross Grain Failures:

$C_c / C_t = 1.01$

$S_c / S_t = 0.76$

$SP_c / SP_t = 0.85$

(b) Failures at Scarfs:

$S_c / C_m = 0.82$

$SP_s / C_m = 1.0$

Where C,S and SP denote control, unplaned and planed beams respectively and the subscripts have the following meaning:

c = mean cross grain failure stress

t = mean tension failure stress

s = mean failure stress at scarf

m = mean group failure stress exclusive compression failure.

TABLE 5 B

Strength Ratios

SERIES X, Y, Z and CW - BASED ON INITIAL FAILURE STRESSES.

$X / CW = 0.80$

$Y / CW = 0.82$

$Z / CW = 0.94$

Where X, Y, Z and CW denote the mean initial group Failure stresses of the respective beam types.

TABLE 6 A

Average Specific Gravity and Moisture Content of SERIES C, S and SP

First Failure Type	Beam Type					
	C		S		SP	
	m.c.,%	sp.gr.	m.c.,%	sp.gr.	m.c.,%	sp.gr.
Tension Failure	12.2	0.56	11.2	0.57	10.7	0.53
Cross Grain	13.2	0.56	10.1	0.54	10.0	0.53
Compression	-	0.50	-	-	-	-
Scarf	-	-	11.1	0.55	10.1	0.51
Group Mean	12.7	0.56	10.6	0.55	10.3	0.53

Moisture Content = (weight of water/dry weight of sample) x 100.

TABLE 6 B

Average Specific Gravity and Moisture Content of SERIES CW, X, Y and Z

Group Means

Beam Type							
CW		X		Y		Z	
m.c,%	sp.gr.	m.c.,%	sp.gr.	m.c.,%	sp.gr.	m.c.,%	sp. gr.
-	0.54	13.0	0.60	12.6	0.59	13.0	0.58

TABLE 7A

Average Moduli of Elasticity of SERIES C, S and SP

(No allowance made for lateral restraint)

	Beam Type		
	C	S	SP
N	25	24	25
$\bar{x}$, 10^6 psi	1.96	2.18	2.23
S, 10^6 psi	0.234	0.250	0.193
V, %	11.9	11.5	8.65

TABLE 7 B

Average Moduli of Elasticity of SERIES CW, X, Y and Z

(No allowance made for lateral restraint)

	BEAM TYPE			
	CW*	X	Y	Z
N	6	6	6	6
$\bar{x}$, 10^6 psi	2.26	2.42	2.25	2.41
S, 10^6 psi	0.157	0.113	0.212	0.235
V, %	6.95	4.67	9.45	9.74

* The one specimen of low specific gravity had a modulus of elasticity of 1.65 x 10^6 psi.

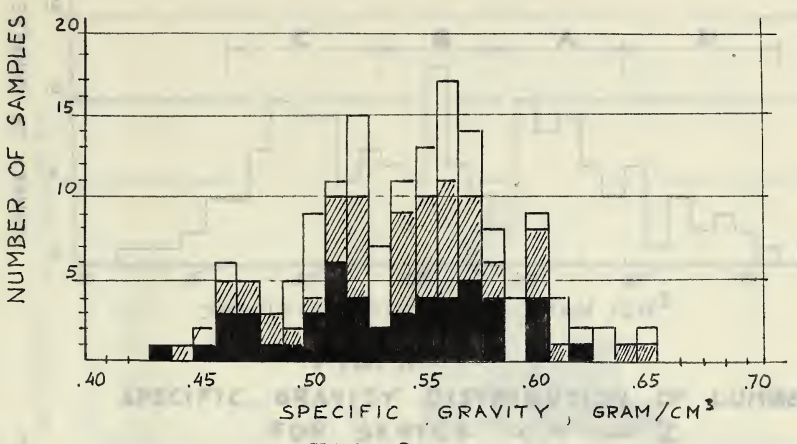


FIG. 3
SPECIFIC GRAVITY DISTRIBUTION OF TOP SAMPLES
BEAM SERIES C, S and SP

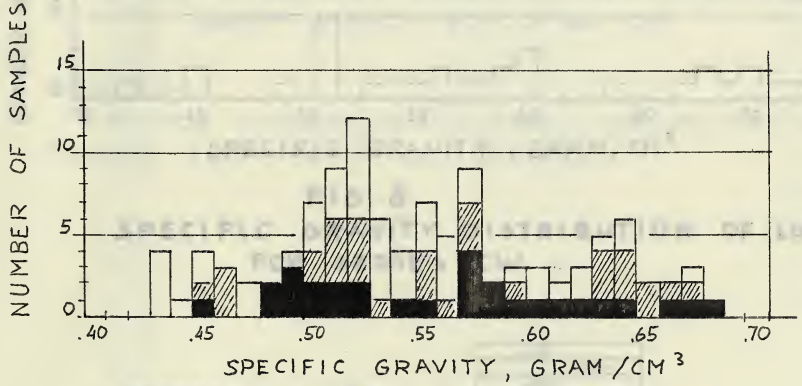


FIG. 4
SPECIFIC GRAVITY DISTRIBUTION OF BOTTOM SAMPLES
BEAM SERIES C, S and SP

LEGEND:
SAMPLE FOR DETERMINATION OF SPECIFIC GRAVITY TAKEN FROM BEAM OF SERIES

C ■
S ▨
SP □

FIG. 3

SPECIFIC GRAVITY DISTRIBUTION OF TOP SAMPLES
BEAM SERIES C, S and SP

FIG. 4

SPECIFIC GRAVITY DISTRIBUTION OF BOTTOM SAMPLES
BEAM SERIES C, S and SP

LEGEND:

SAMPLE FOR DETERMINATION OF SPECIFIC GRAVITY
TAKEN FROM BEAM OF SERIES

C
S
SP

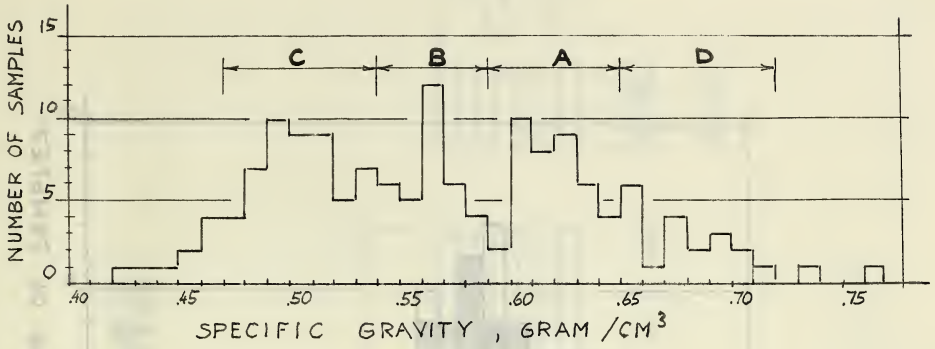


FIG. 5
SPECIFIC GRAVITY DISTRIBUTION OF LUMBER
FOR SERIES X, Y and Z

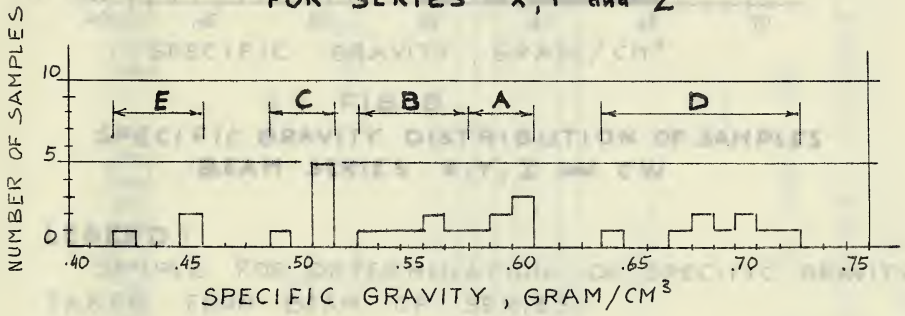
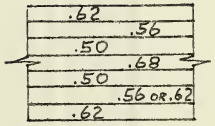
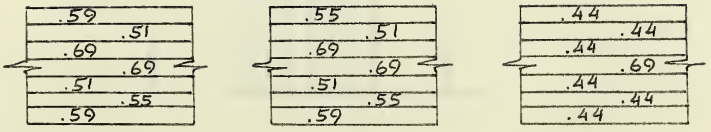


FIG. 6
SPECIFIC GRAVITY DISTRIBUTION OF LUMBER
FOR SERIES CW

SERIES X, Y and Z



SERIES CW



TYPE A TYPE B TYPE C

FIG. 7
LAYUP OF LAMINATIONS ACCORDING TO
SPECIFIC GRAVITY

FIG. 5

SPECIFIC GRAVITY DISTRIBUTION OF LUMBER
FOR SERIES X, Y and Z

FIG. 6

SPECIFIC GRAVITY DISTRIBUTION OF LUMBER
FOR SERIES CM

FIG. 7

LAYUP OF LAMINATIONS ACCORDING TO
SPECIFIC GRAVITY

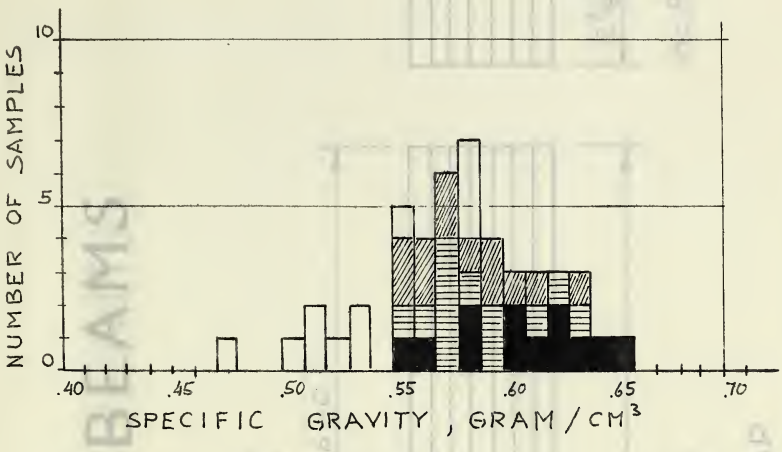


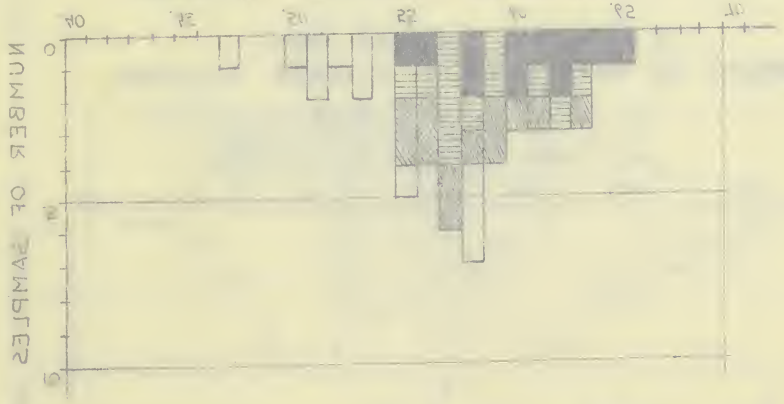
FIG. 8

SPECIFIC GRAVITY DISTRIBUTION OF SAMPLES
BEAM SERIES X, Y, Z and CW

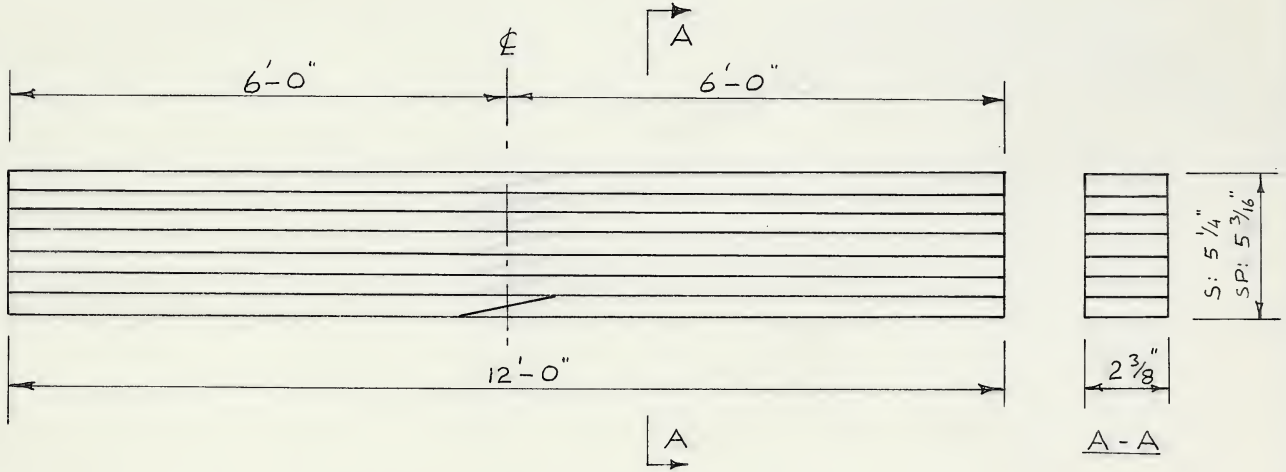
LEGEND:

SAMPLE FOR DETERMINATION OF SPECIFIC GRAVITY TAKEN FROM BEAM OF SERIES:

X ■
Y ▤
Z ▨
CW □


CM
Z
Y
X
TAKEN FROM BEAM OF SERIES :
SAMPLE FOR DETERMINATION OF SPECIFIC GRAVITY
LEGEND :
BEAM SERIES X, Y, Z and CM
SPECIFIC GRAVITY DISTRIBUTION OF SAMPLES
FIG. 8
SPECIFIC GRAVITY (GRAM / CM3)
SEQUENCE OF NUMBER

LAMINATED WOOD BEAMS



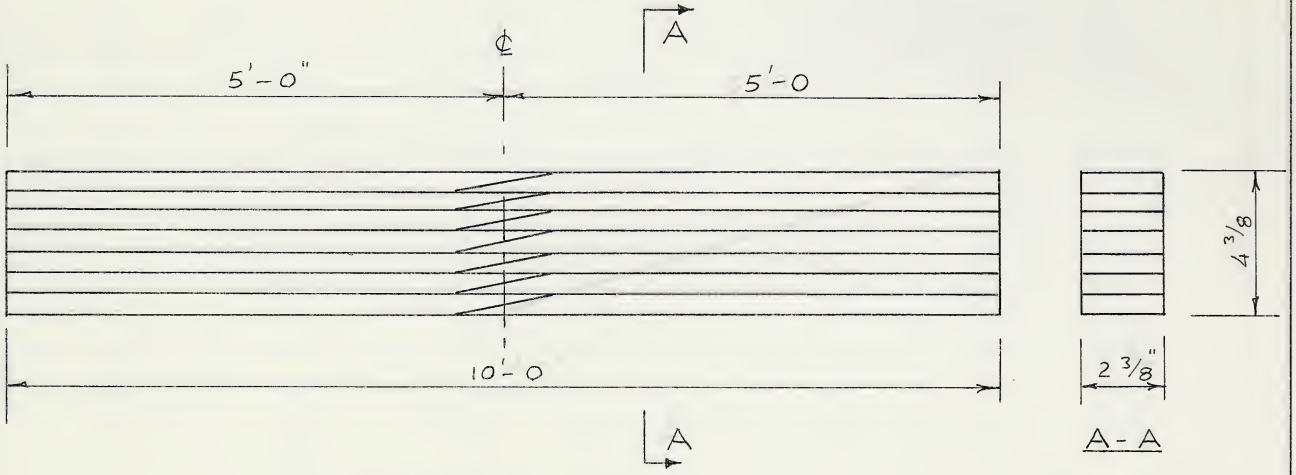
TYPE S and SP

PLAIN SCARF JOINT

FIG. 9

LAMINATED WOOD BEAMS

LAMINATED WOOD BEAMS



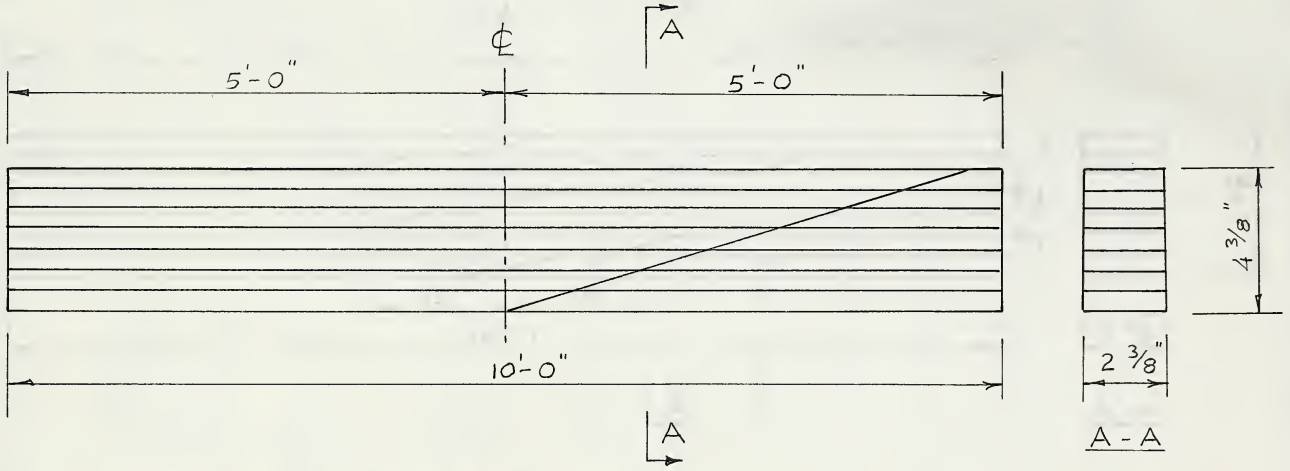
TYPE X

PLAIN SCARF JOINTS, STACKED

FIG. 10

LAMINATED WOOD BEAMS

LAMINATED WOOD BEAMS



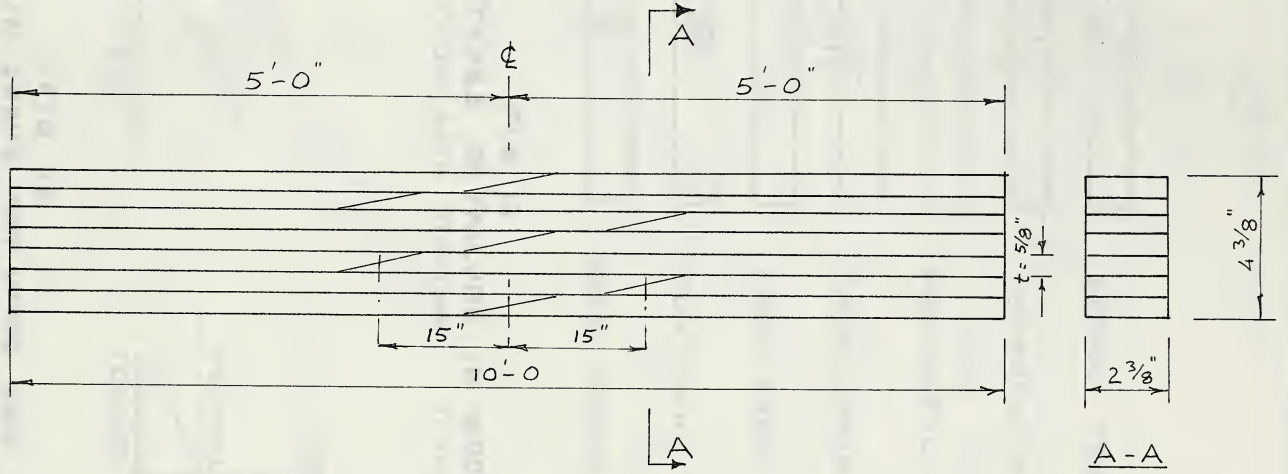
TYPE Y

PLAIN SCARF JOINTS
FORMING AN INCLINED PLANE

FIG. 11

LAMINATED WOOD BEAMS

LAMINATED WOOD BEAMS



TYPE Z

PLAIN SCARF JOINTS

SPACED AT 24 t

FIG. 12

LAMINATED WOOD BEAMS

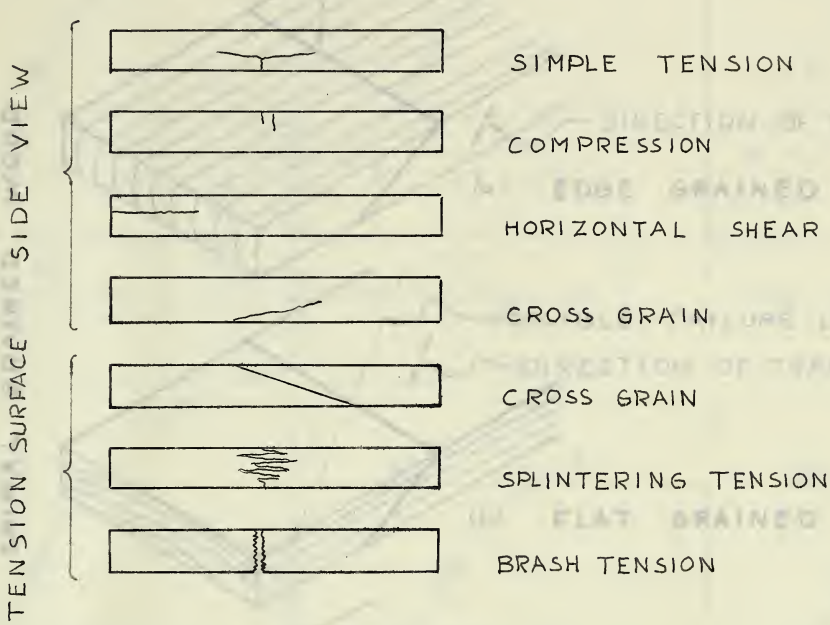


FIG. 13
TYPES OF FAILURE IN WOOD
FROM ASTM STANDARD D 143 - 52

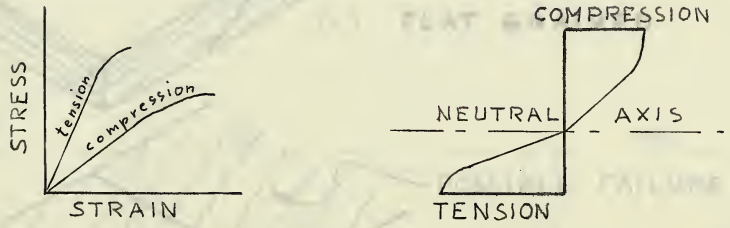


FIG. 15
STRESS - STRAIN CURVE FOR WOOD AND THEORETICAL FLEXURAL STRESS DISTRIBUTION
ACCORDING TO BACH AND BAUMANN (2)

FIG. 13
TYPES OF FAILURE IN WOOD
FROM ASTM STANDARD D 143 - 52

FIG. 15
STRESS - STRAIN CURVE FOR WOOD AND THEORETICAL FLEXURAL STRESS DISTRIBUTION
ACCORDING TO BACH AND BAUMANN [2]

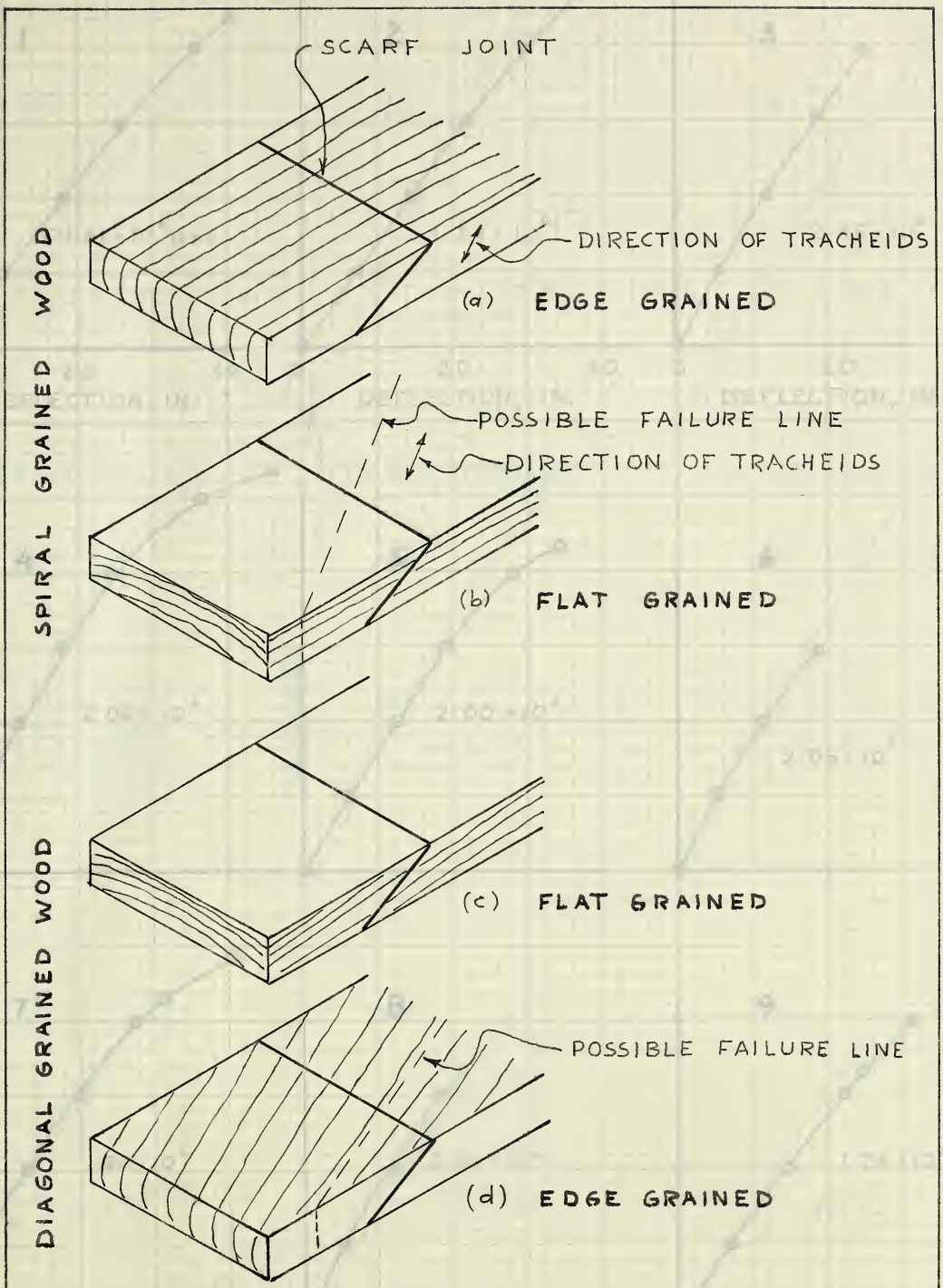


FIG. 16
EFFECT OF CROSS GRAIN ON FAILURE AT THE SCARF JOINT

NOTE : CUMULATIVE EFFECT ONLY IN CASES (a) AND (c)

FIG. 16
EFFECT OF CROSS GRAIN ON FAILURE AT THE SCARF JOINT

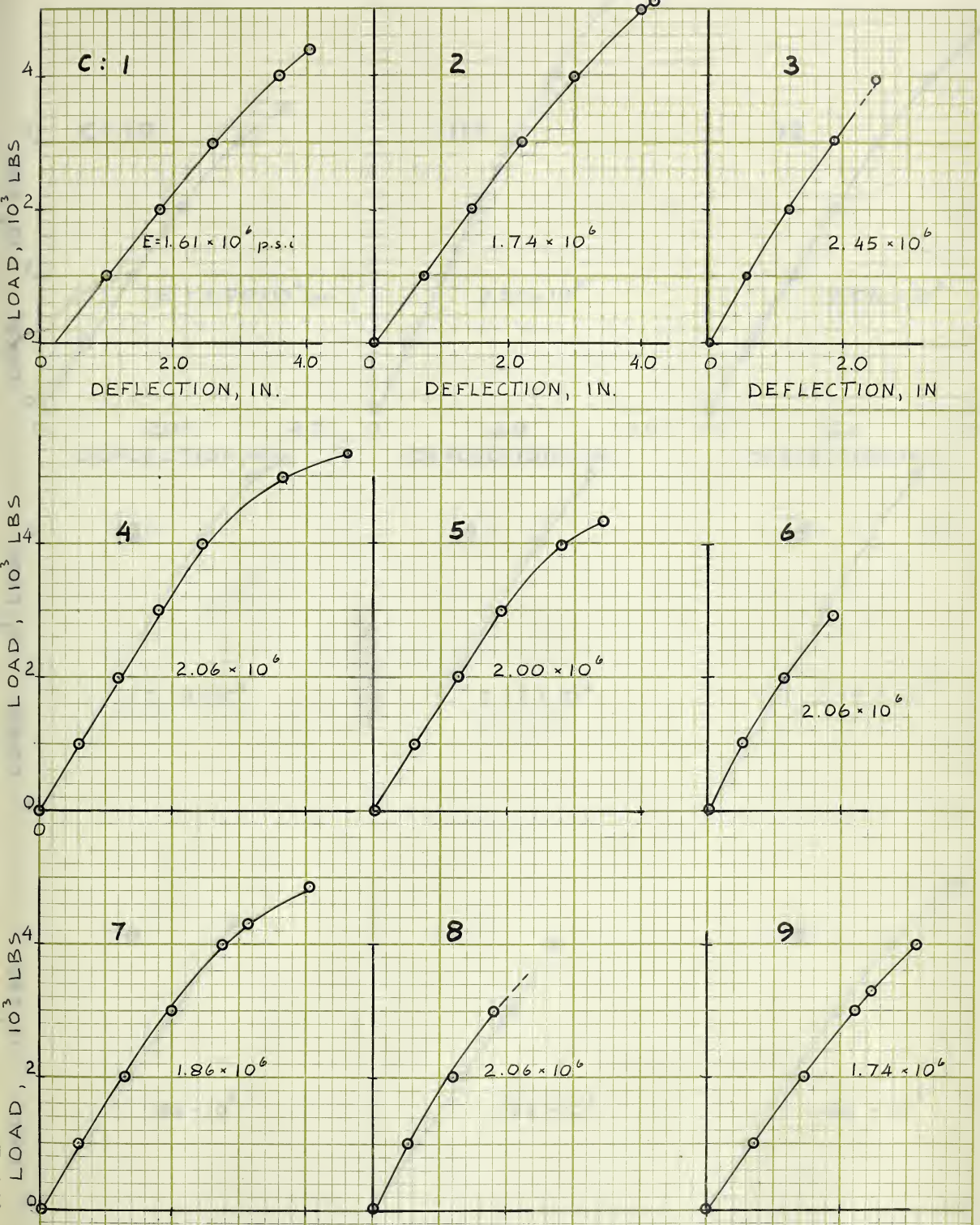
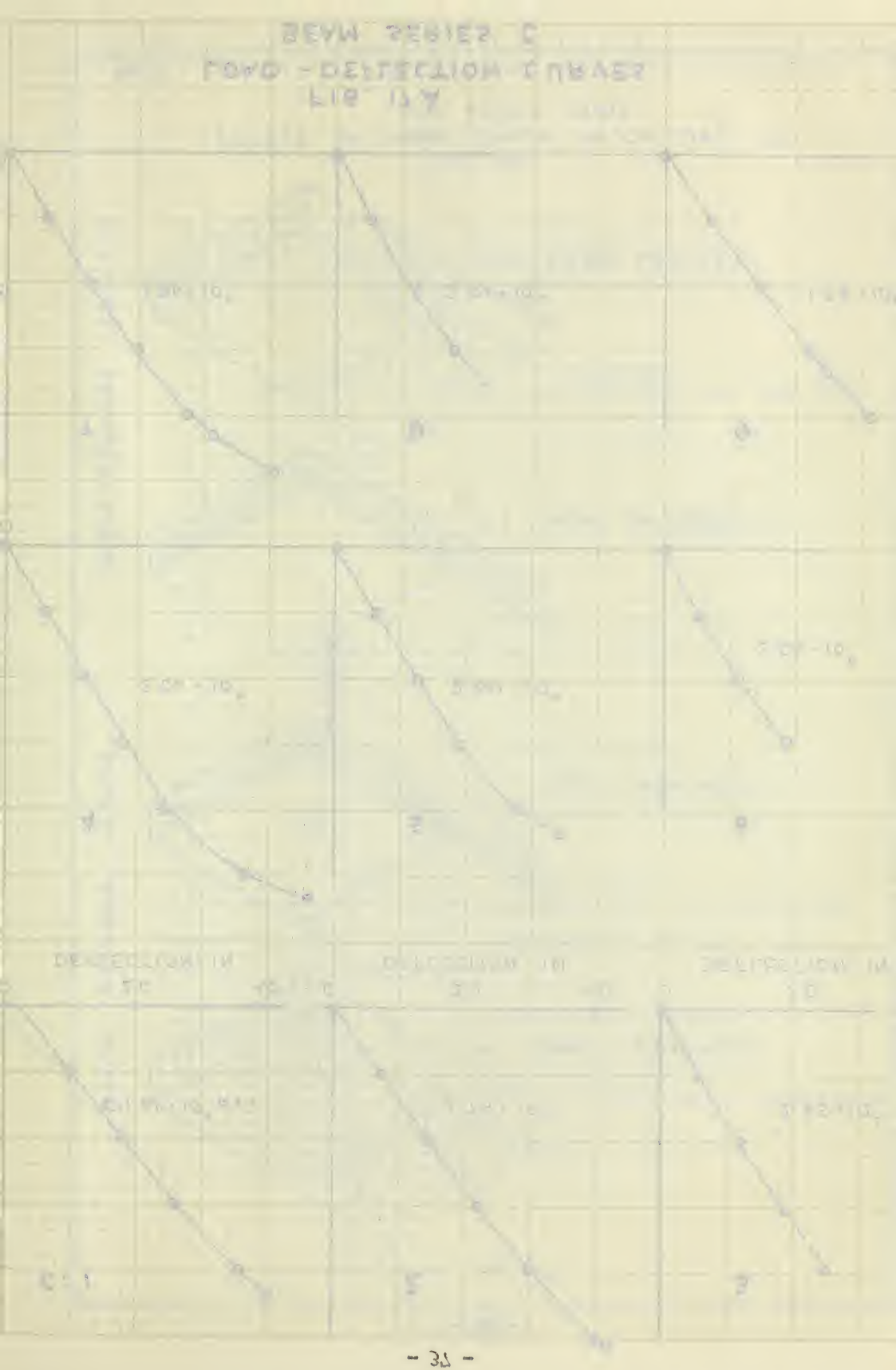


FIG. 17 A
LOAD - DEFLECTION CURVES
BEAM SERIES C



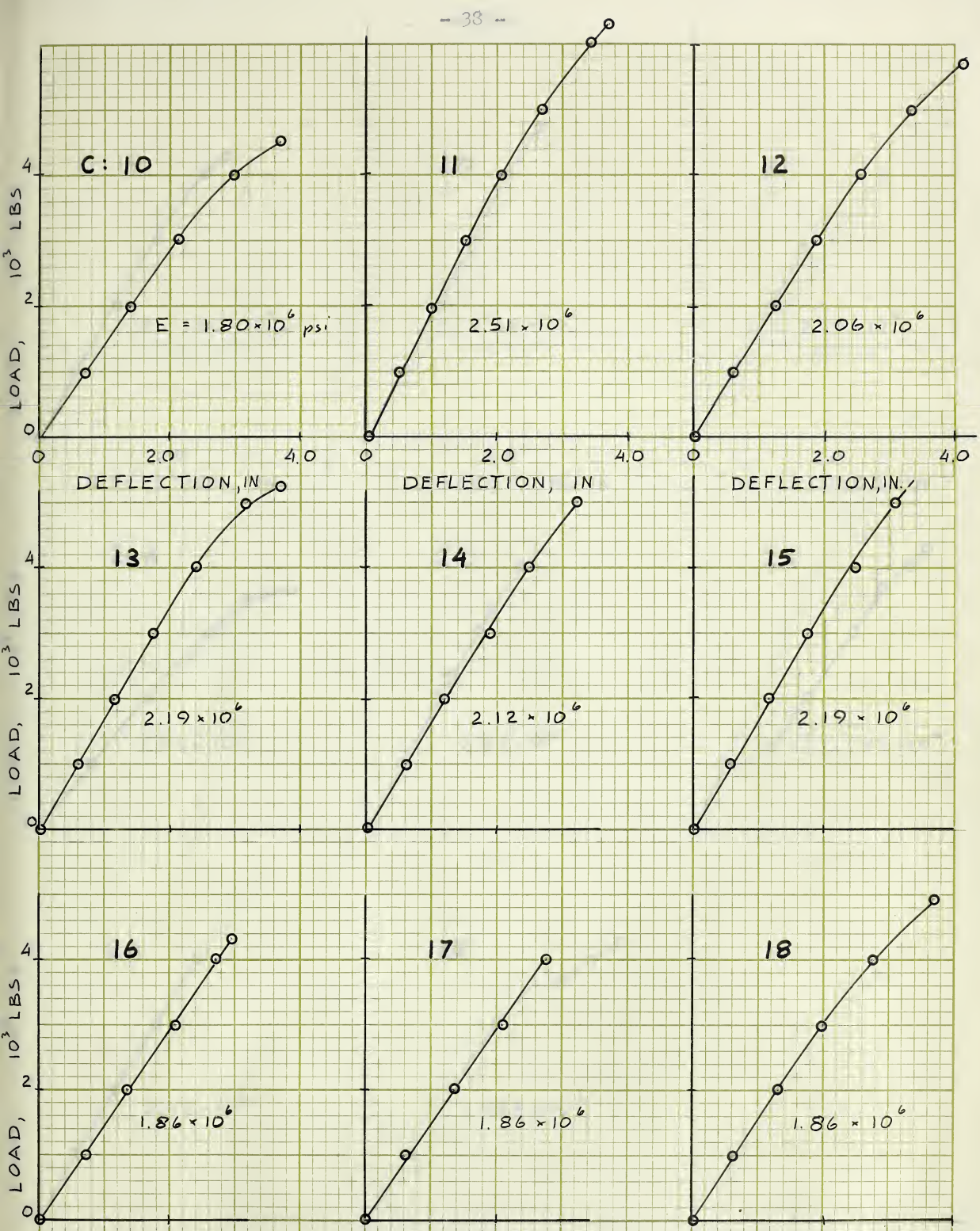
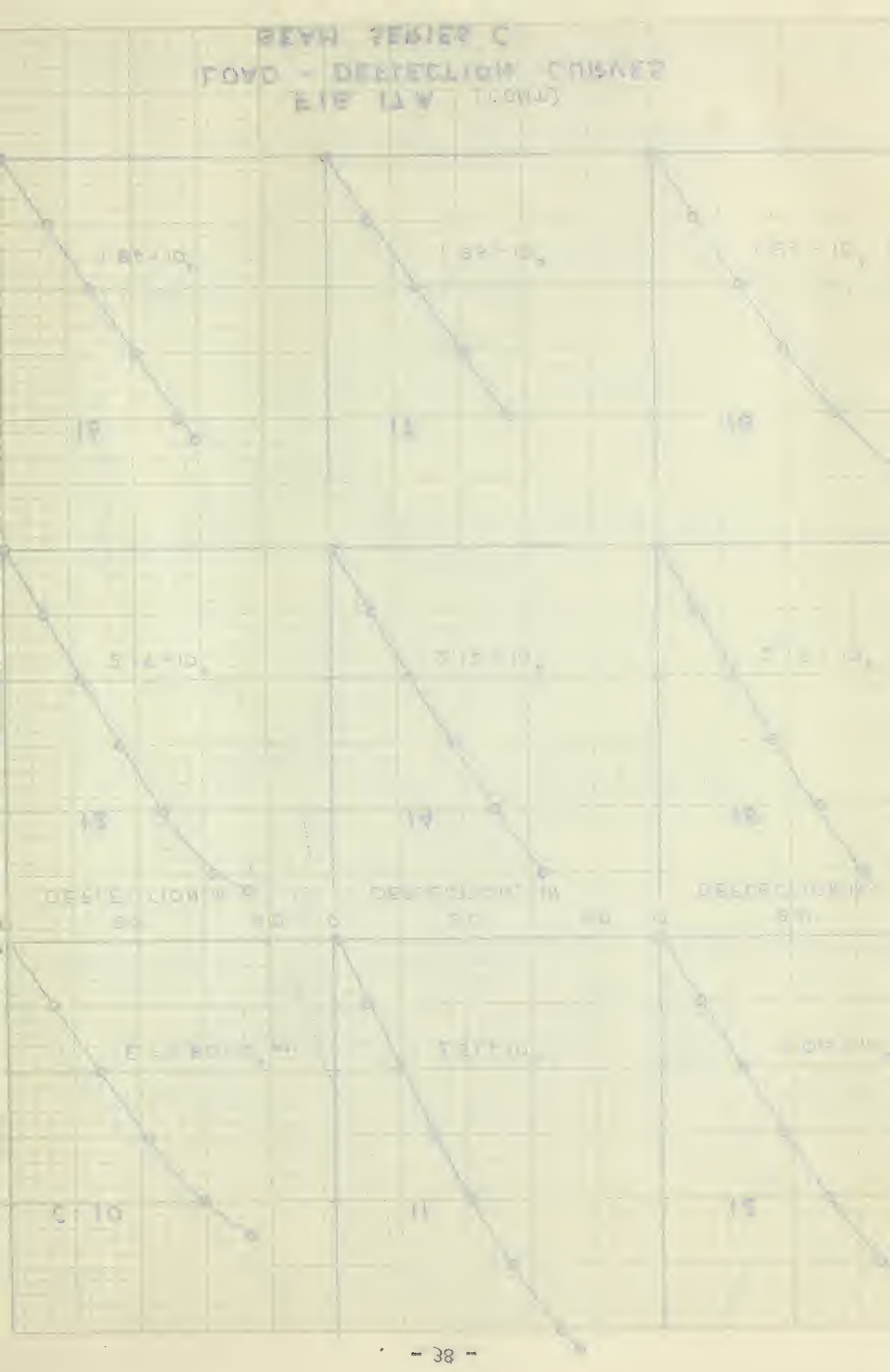


FIG. 17 A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES C



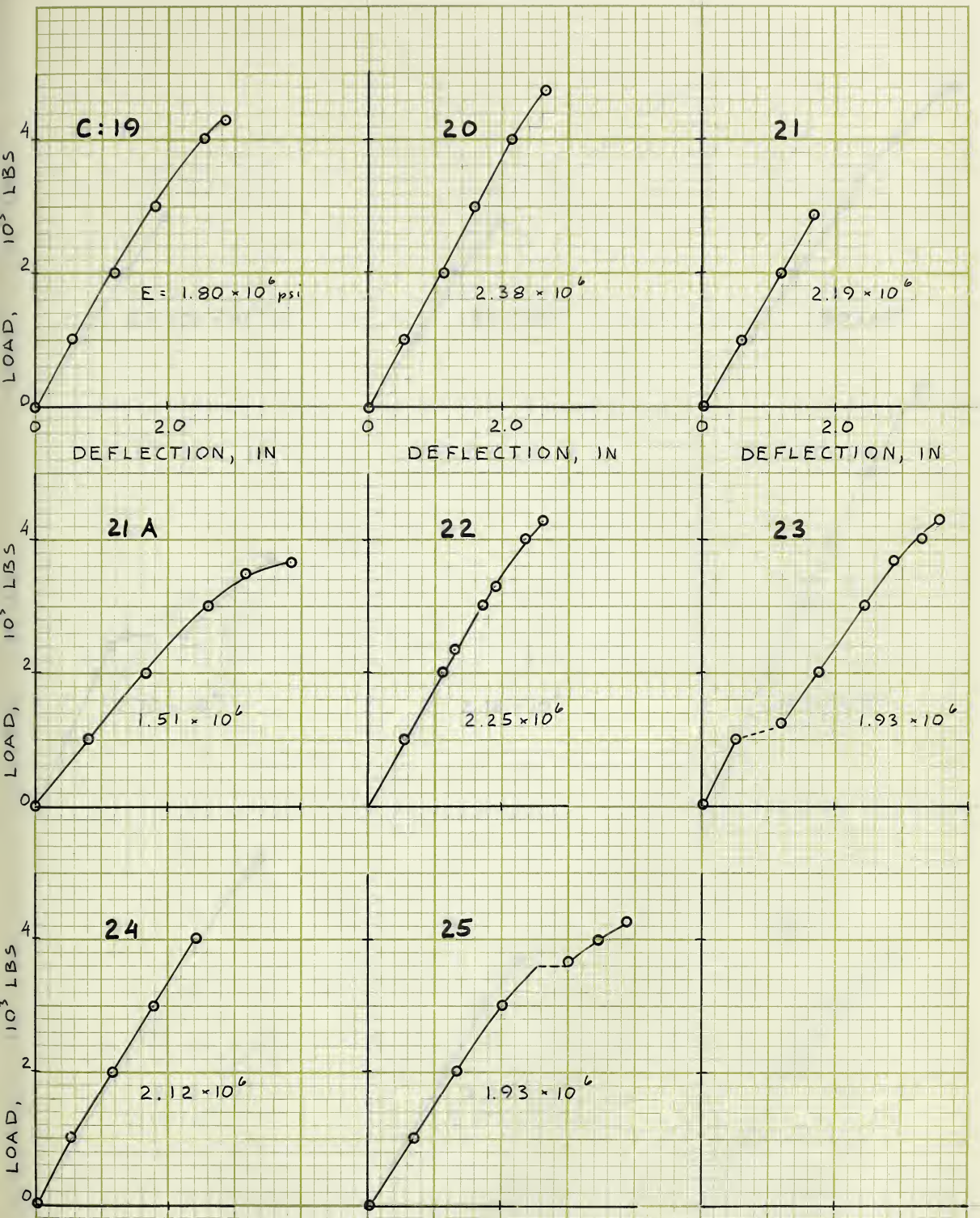


FIG. 17 A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES C

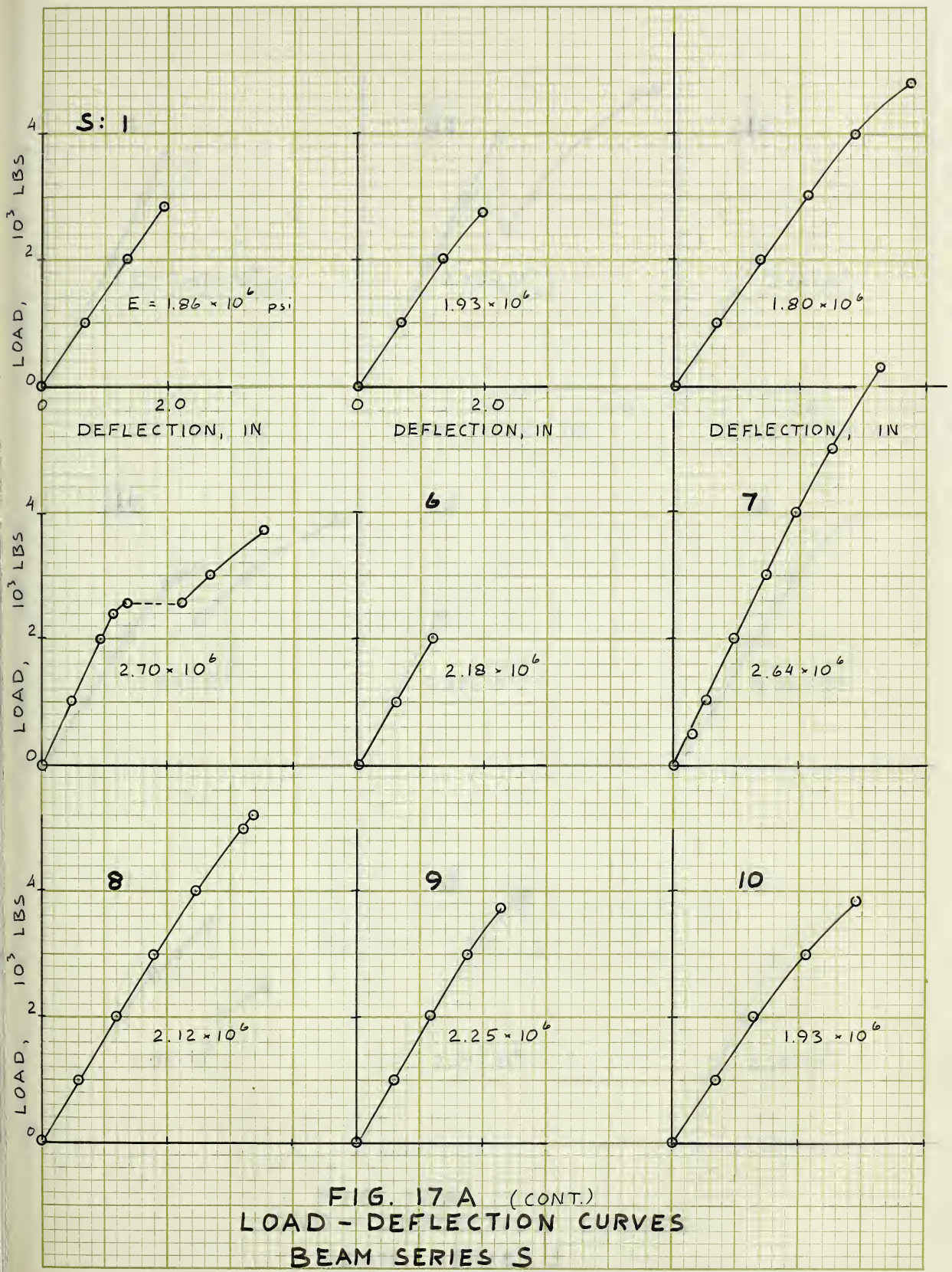


FIG. 17 A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES S

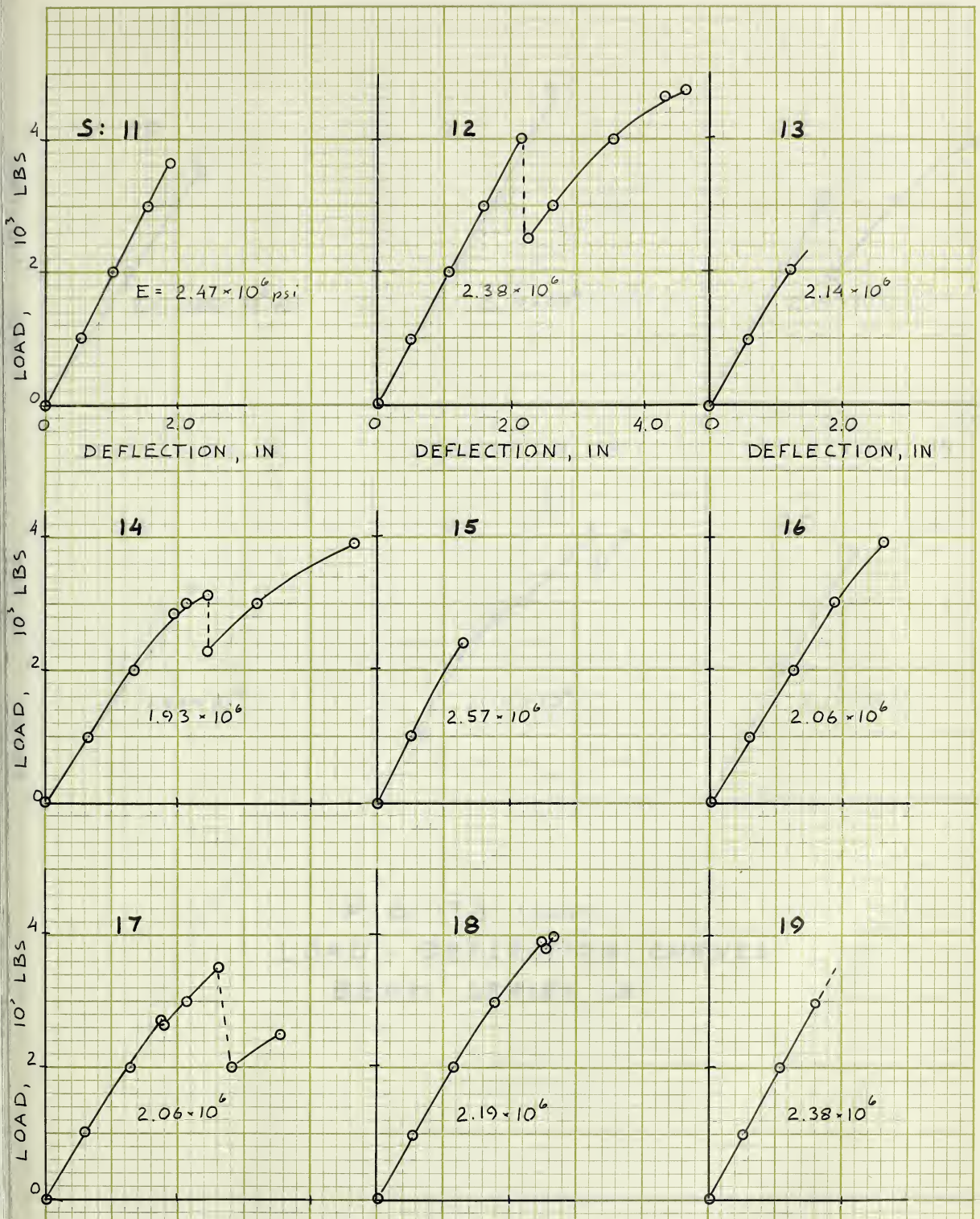
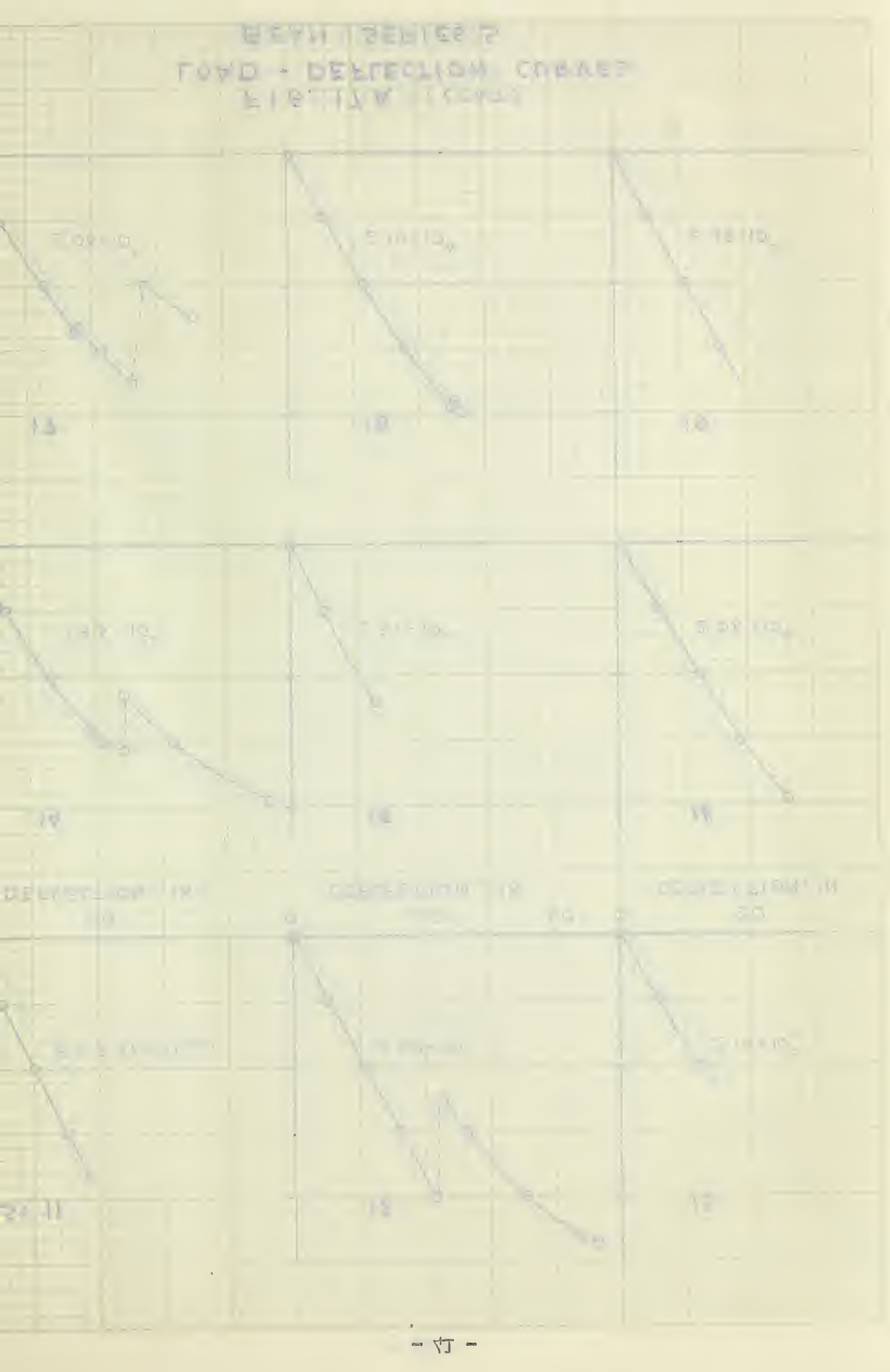


FIG. 17A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES S



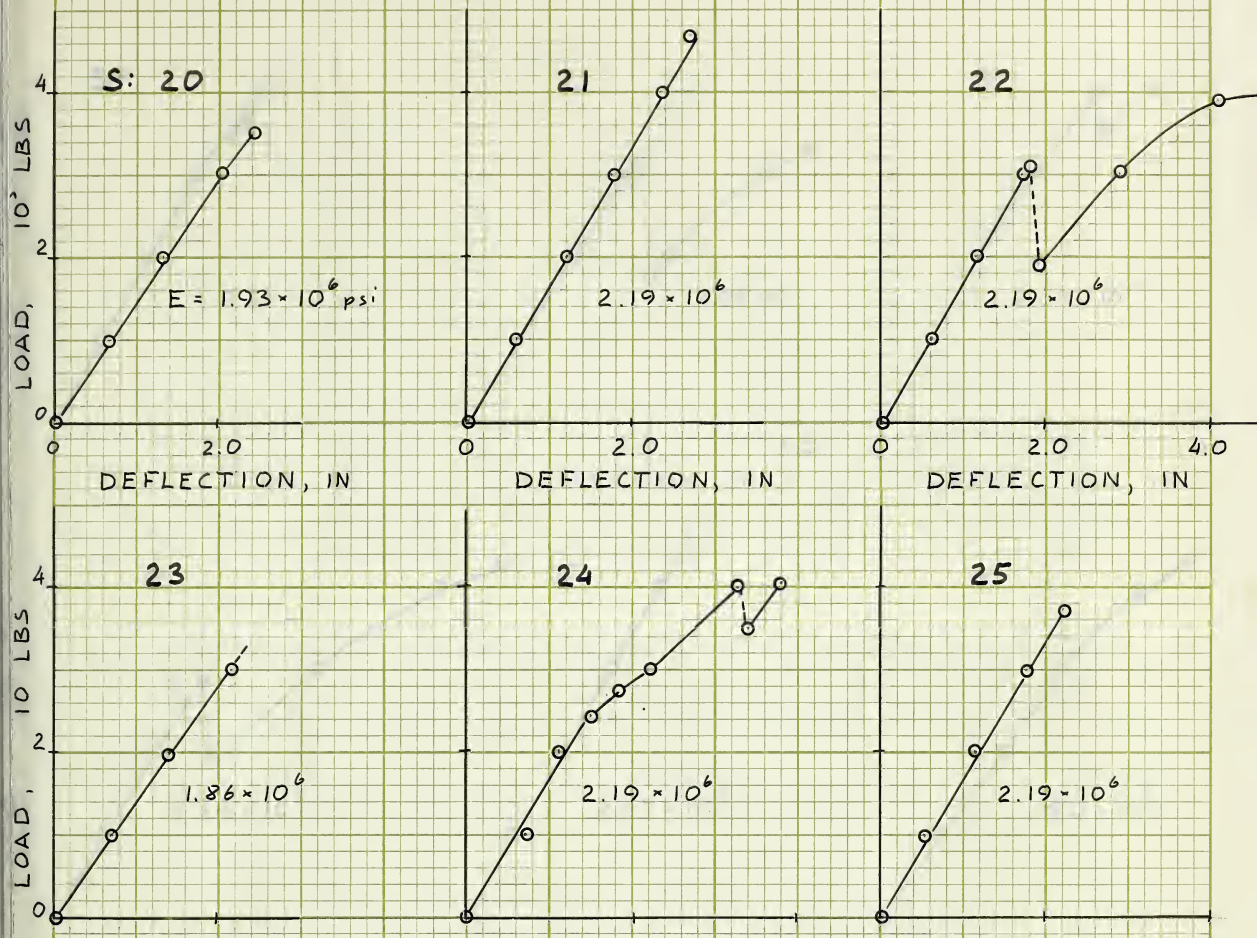


FIG. 17A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES S

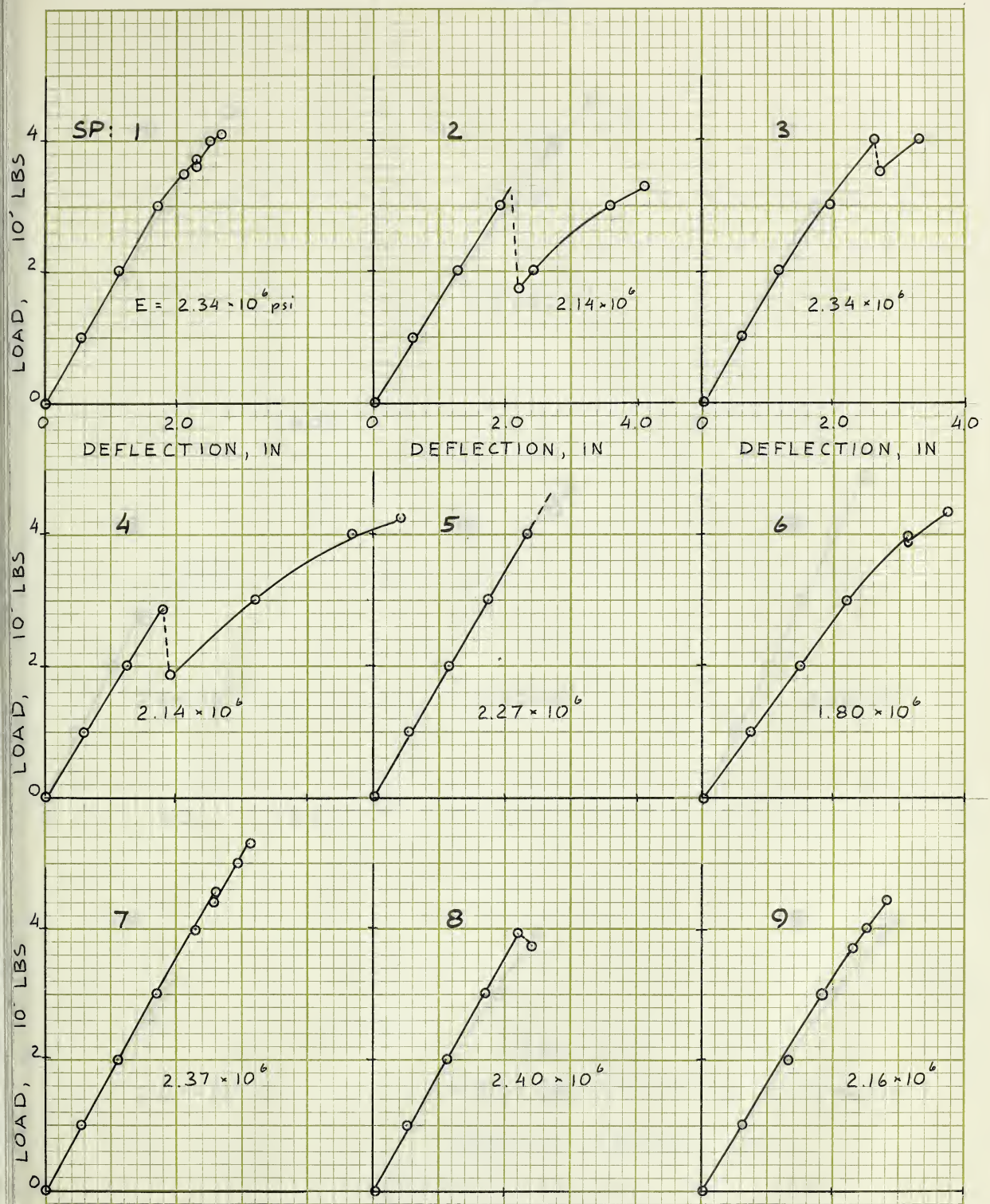


FIG. 17 A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES SP

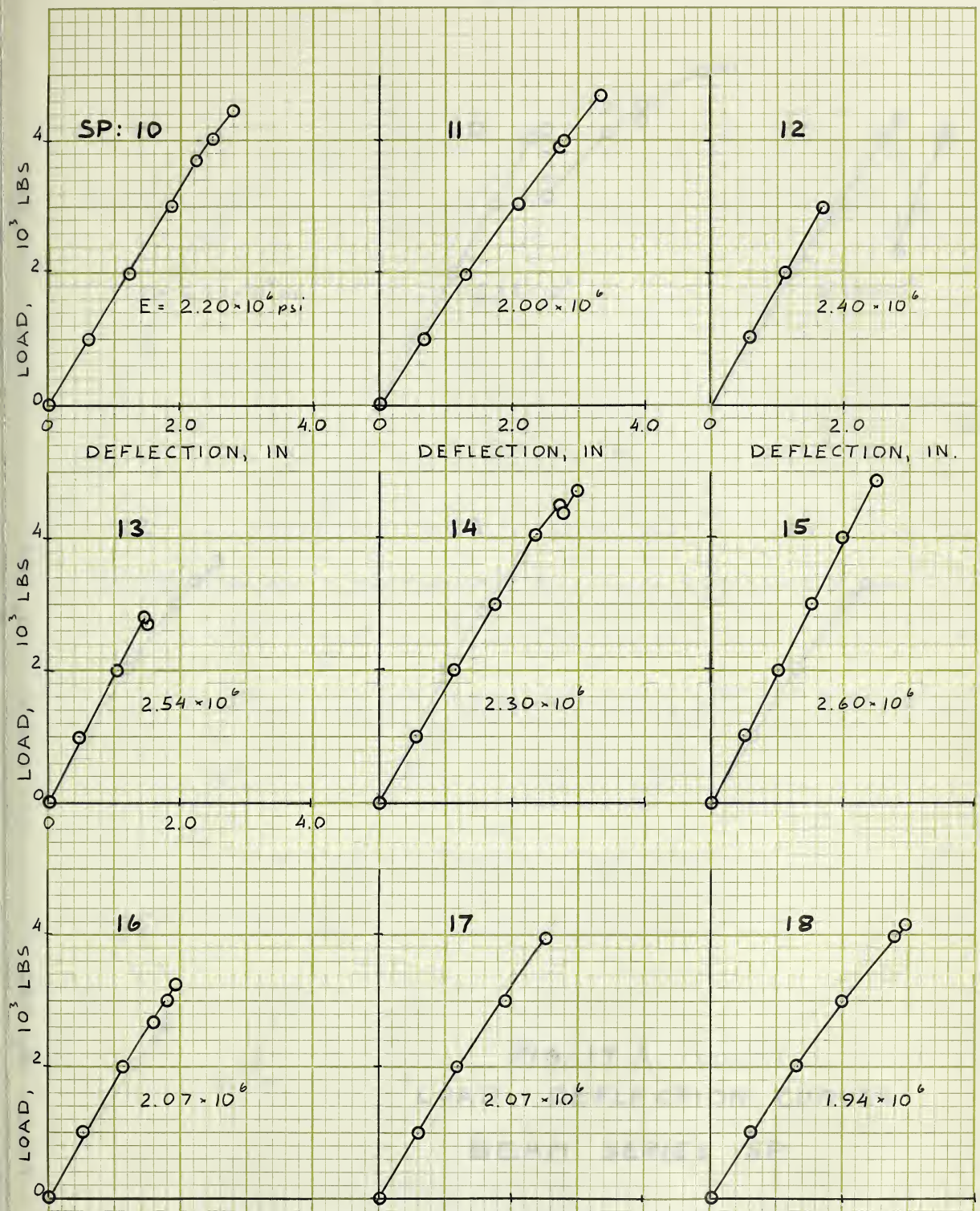


FIG. 17 A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES SP

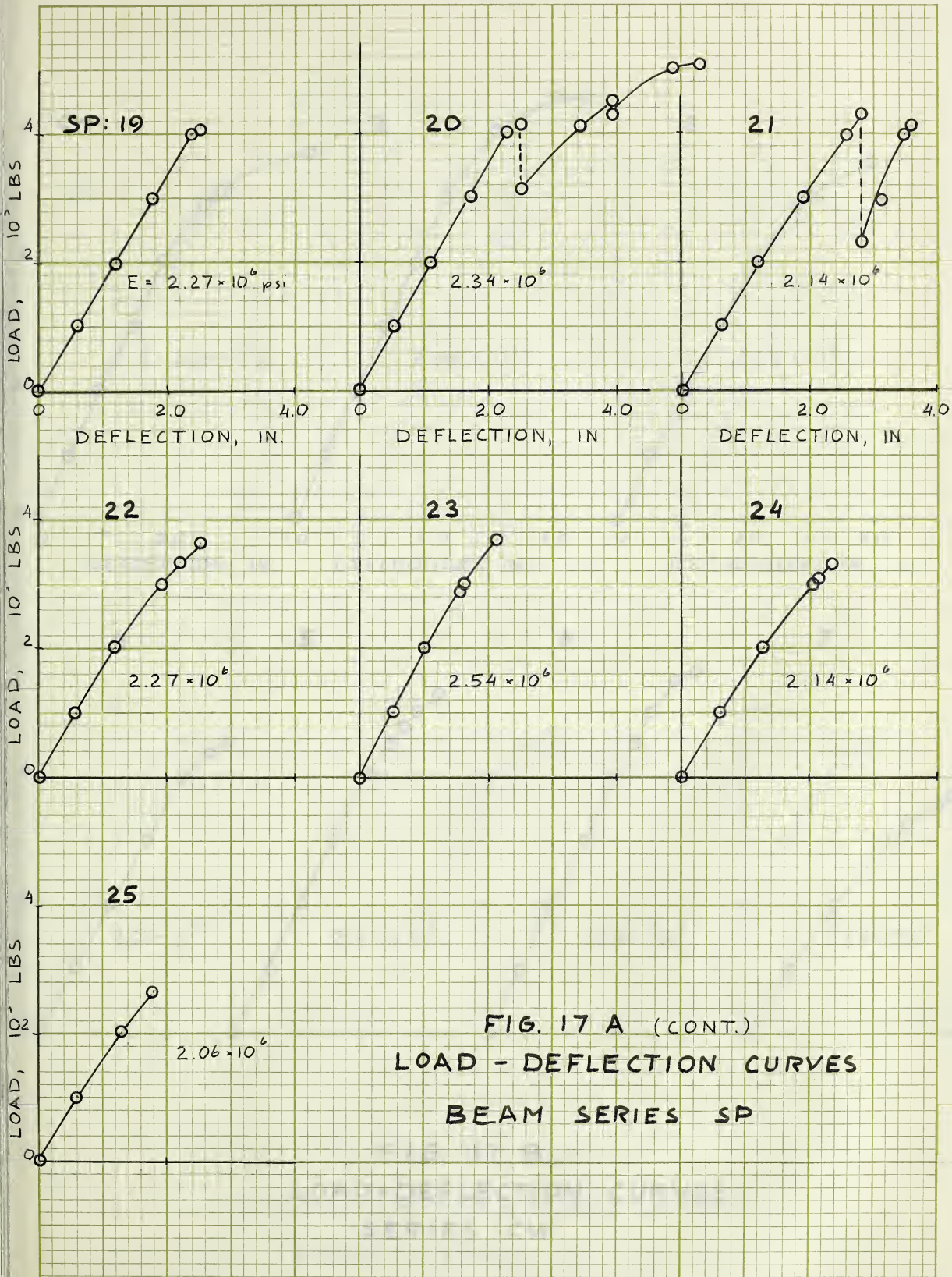


FIG. 17 A (CONT.)
LOAD - DEFLECTION CURVES
BEAM SERIES SP

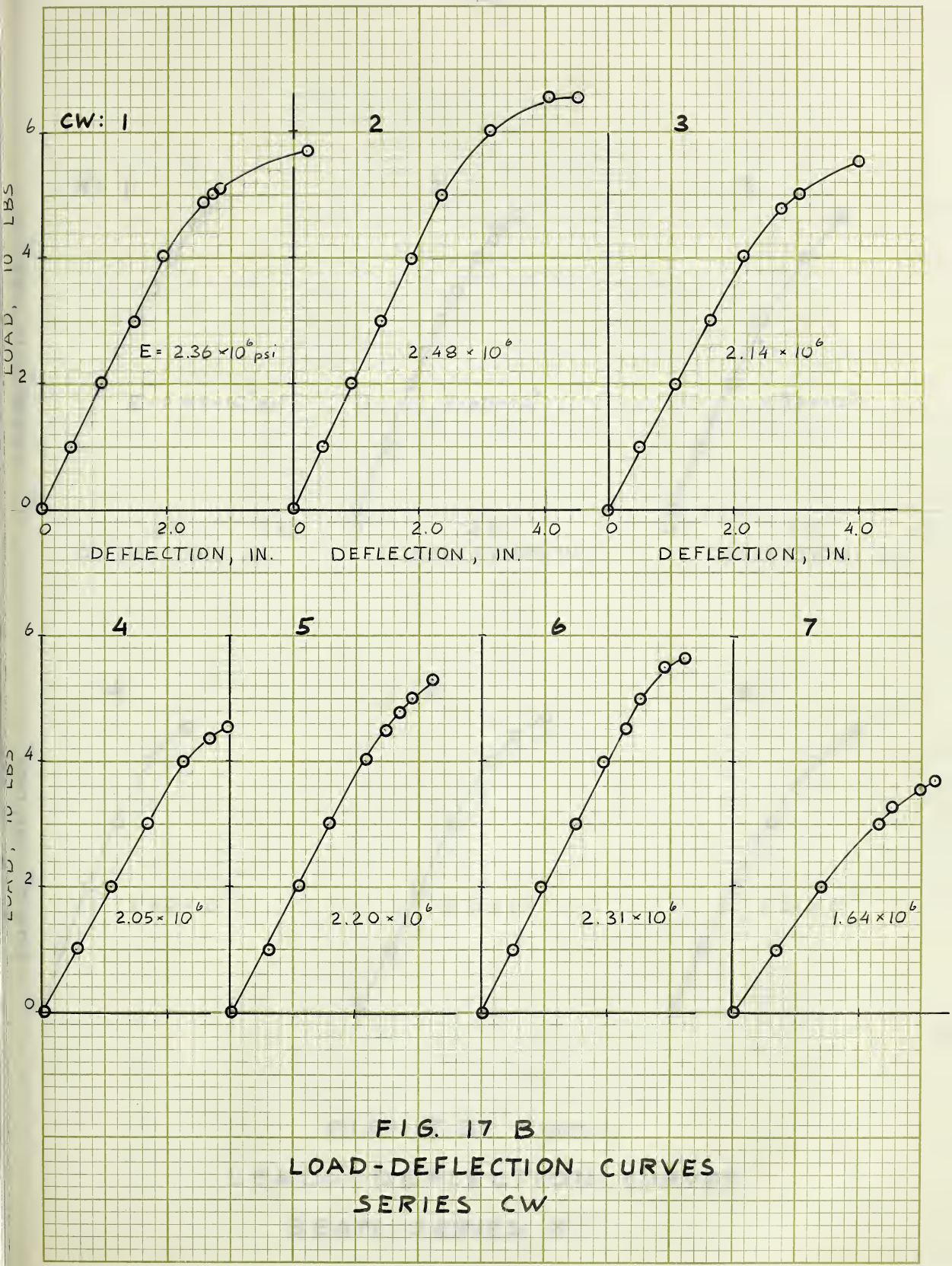


FIG. 17 B
LOAD-DEFLECTION CURVES
SERIES CW

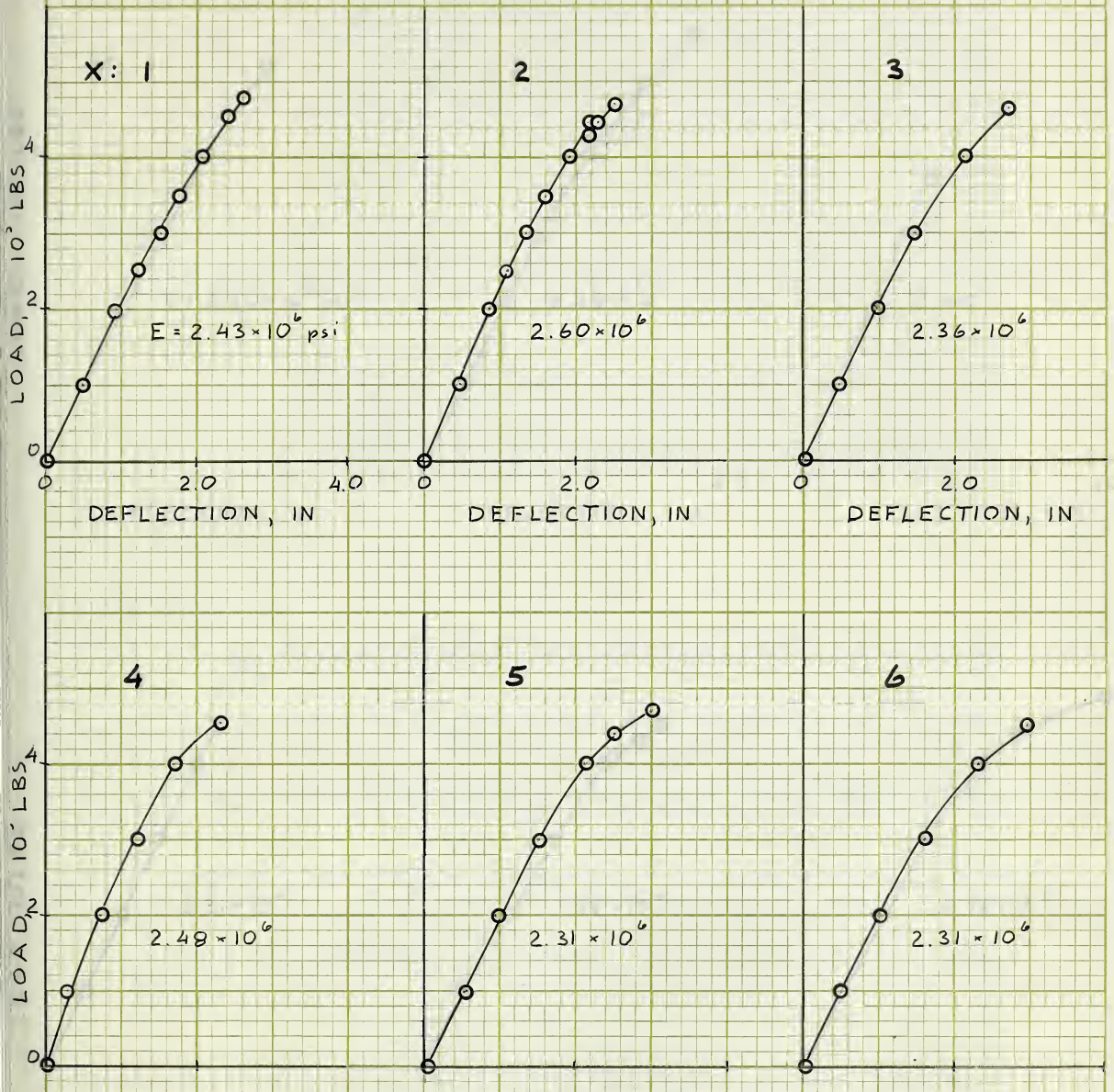


FIG. 17 B (CONT.)

LOAD - DEFLECTION CURVES

BEAM SERIES X

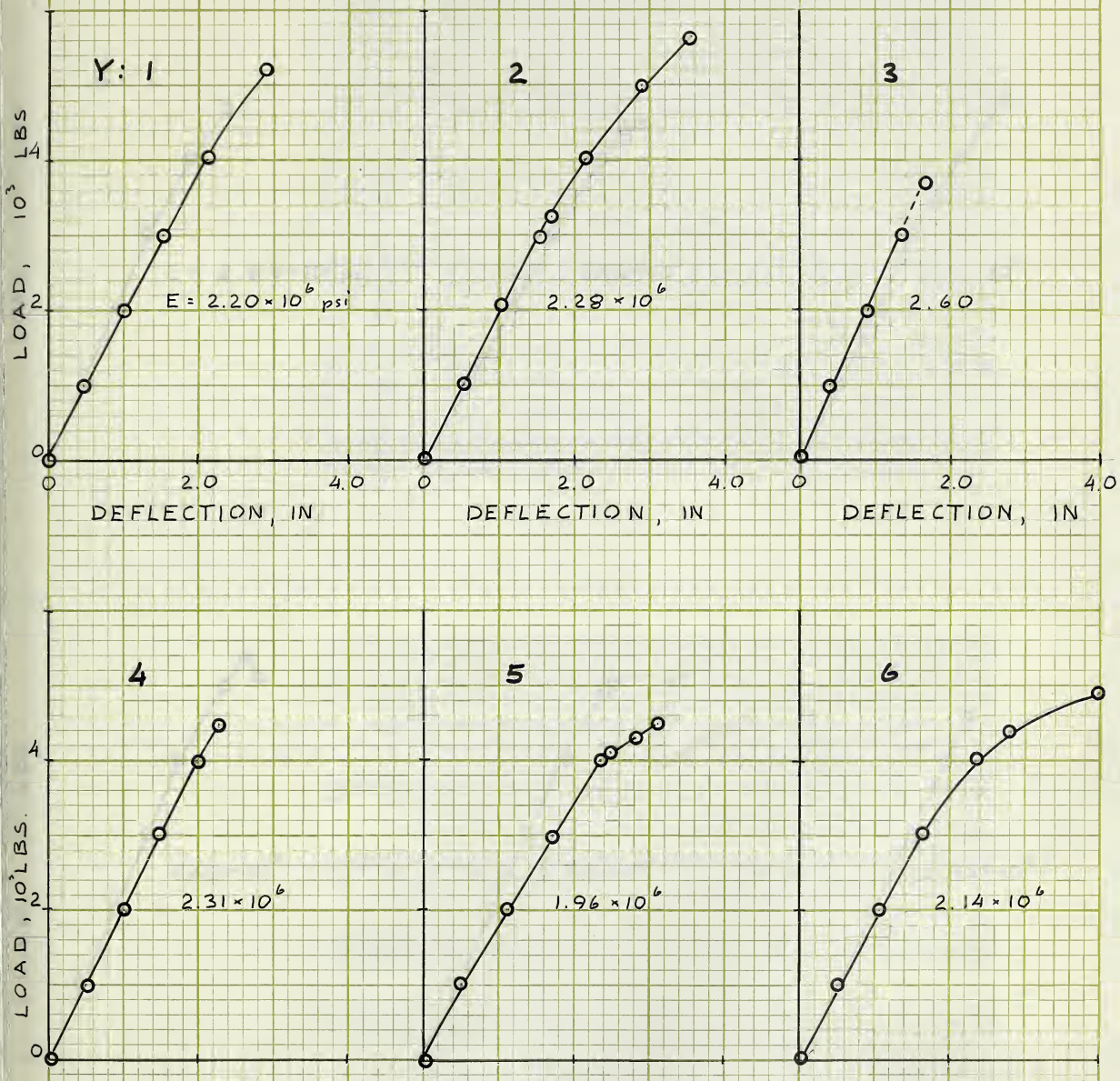
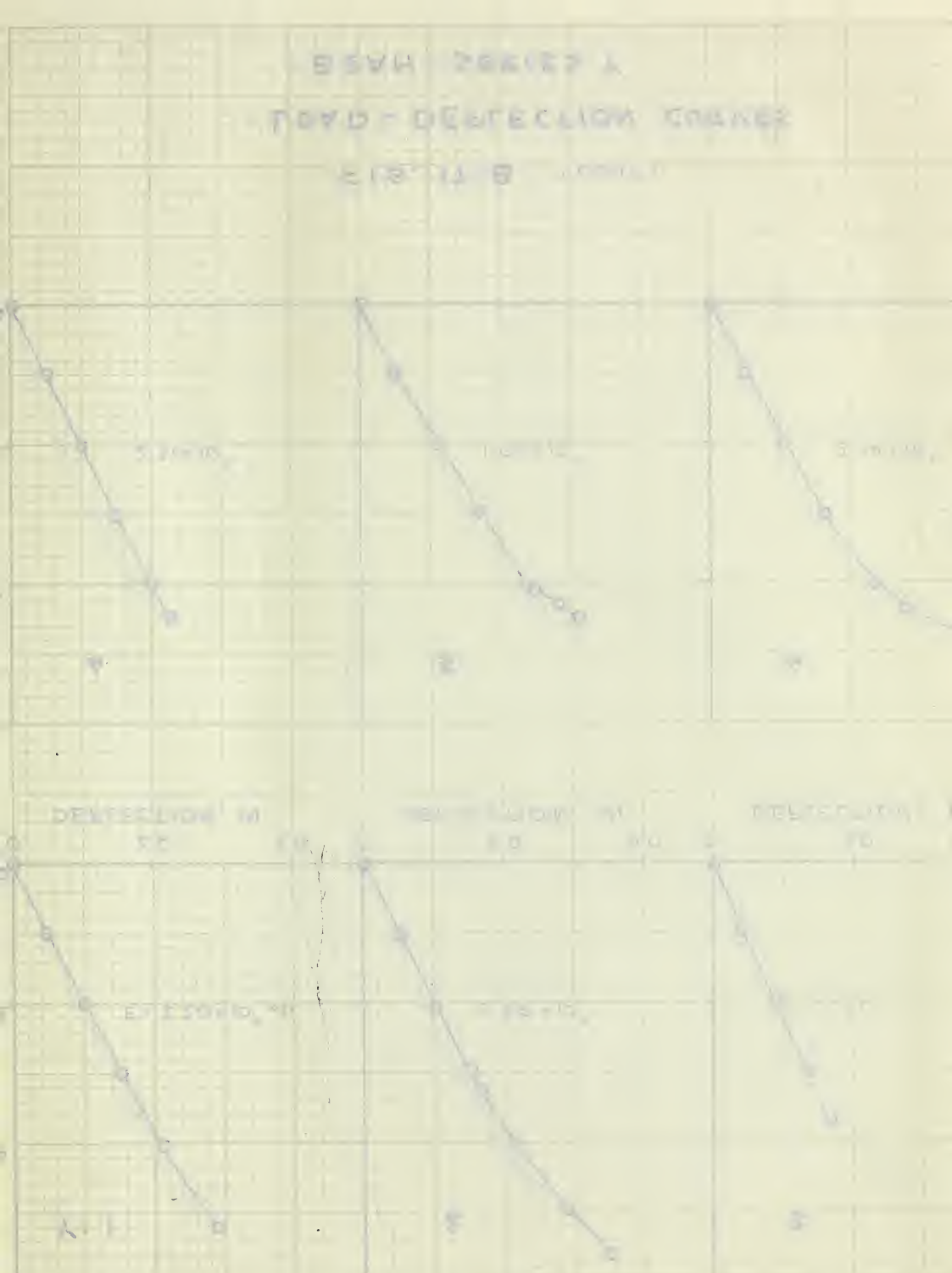


FIG. 17 B (CONT.)

LOAD - DEFLECTION CURVES

BEAM SERIES Y



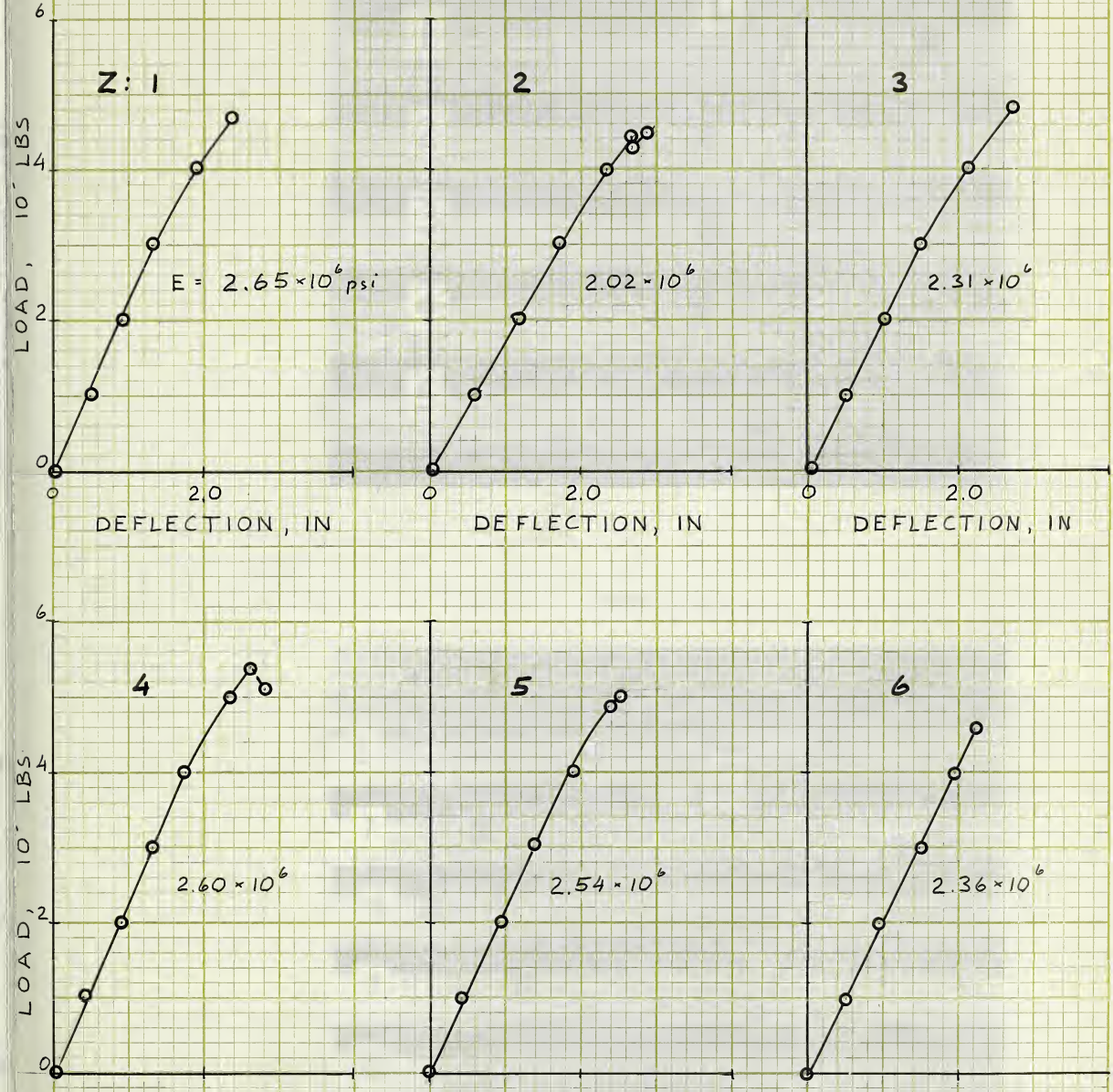
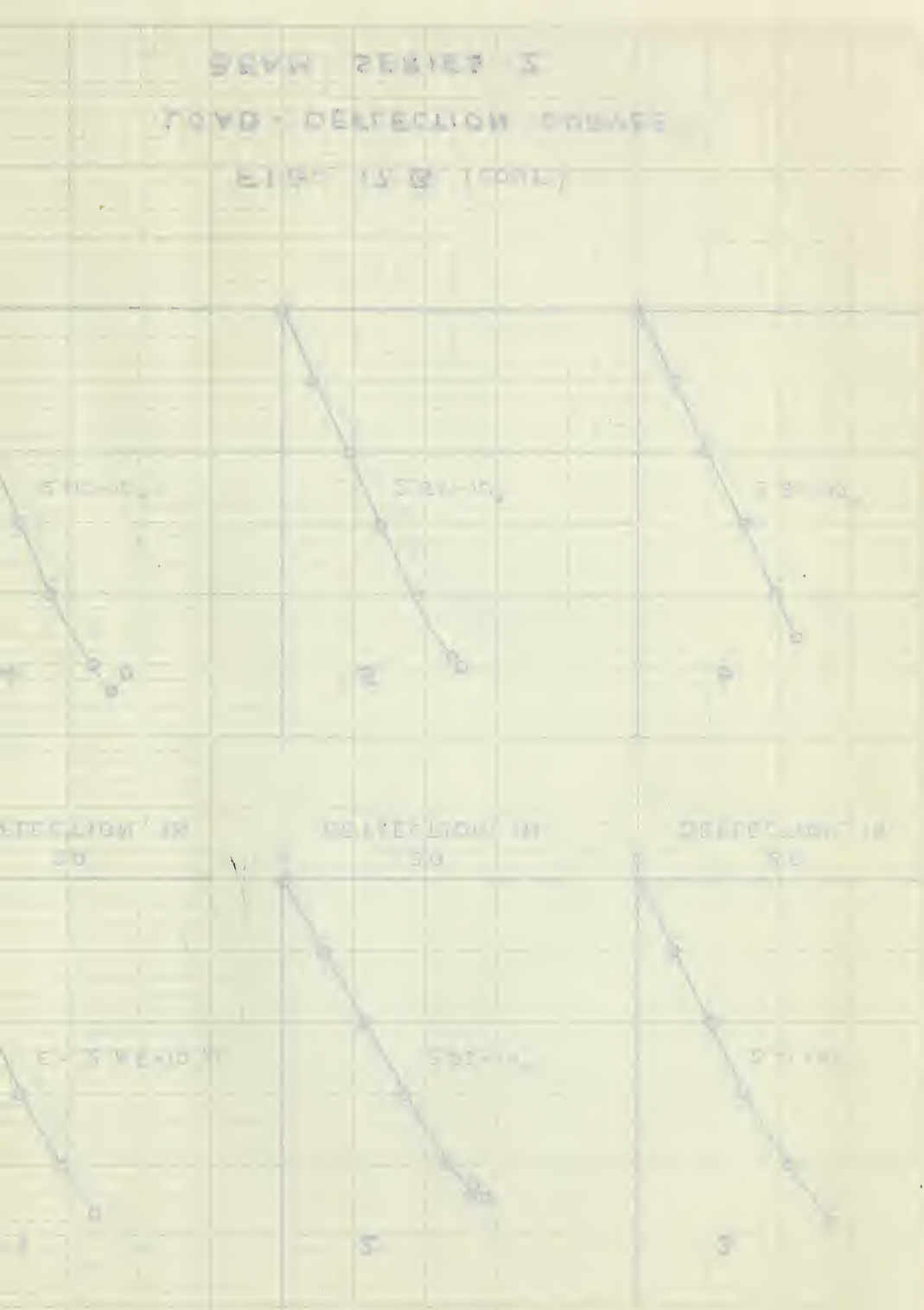
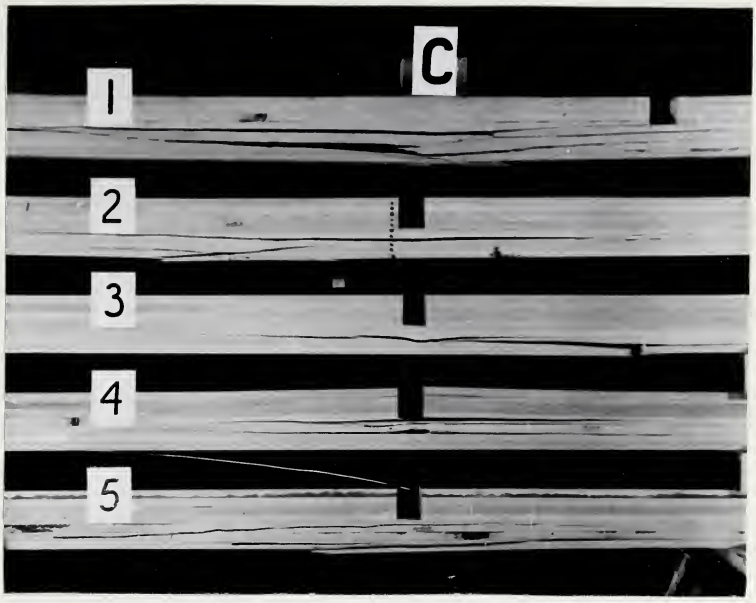


FIG. 17 B (CONT.)

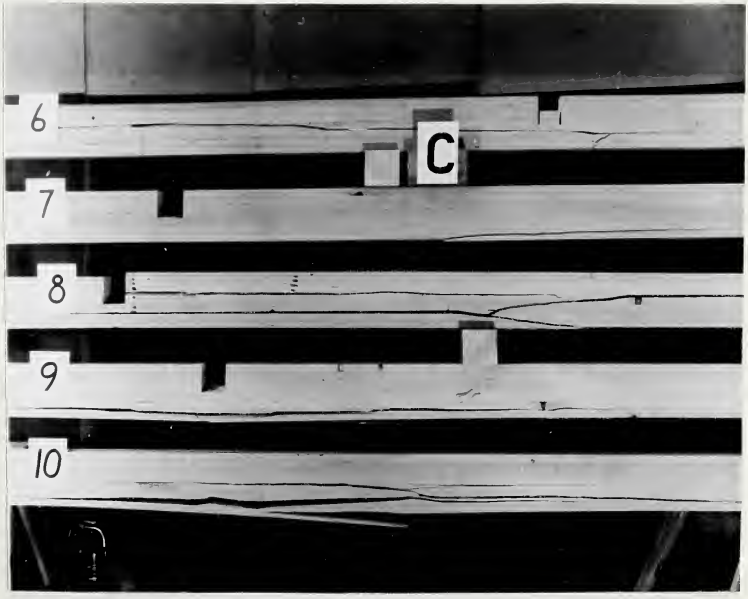
LOAD - DEFLECTION CURVES

BEAM SERIES Z



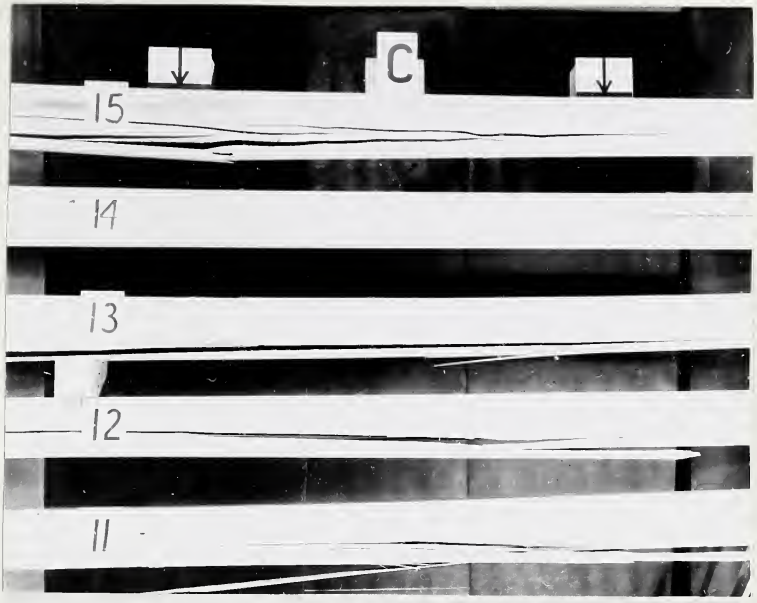


Beams C 1-5

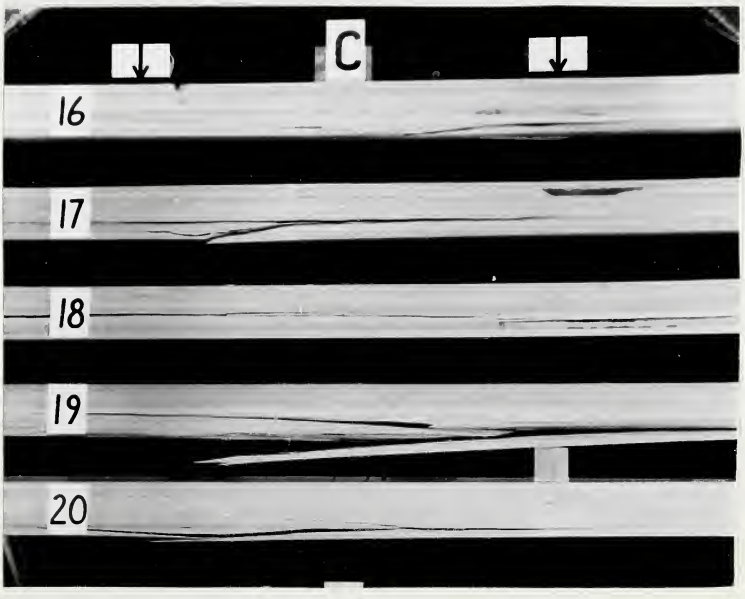


Beams C 6-10

Fig. 18 A

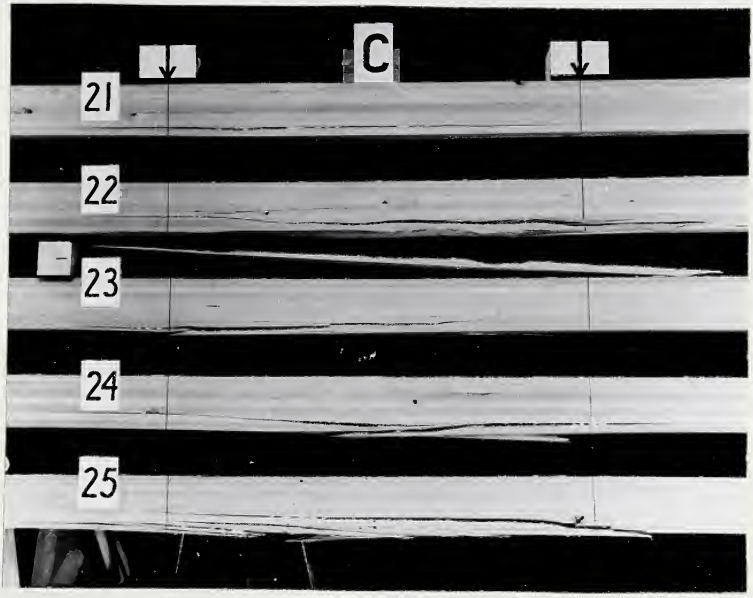


Beams C 11-15



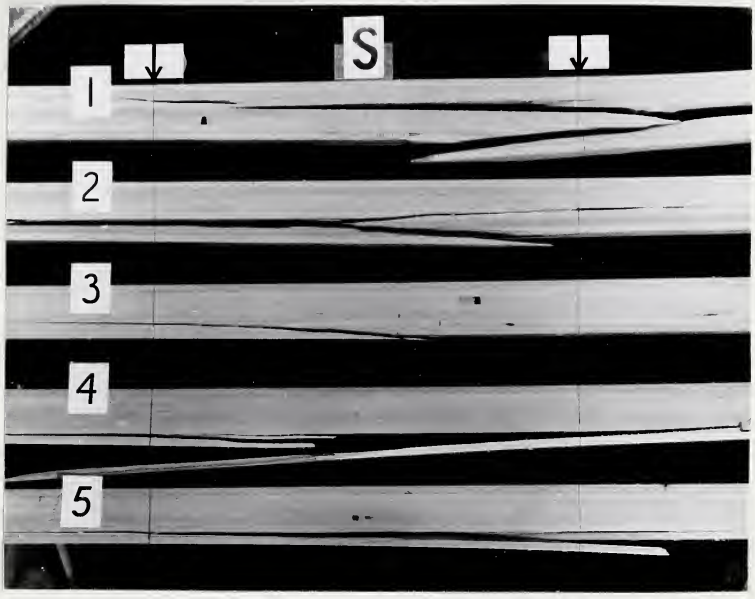
Beams C 16-20

Fig. 18 A (Continued)

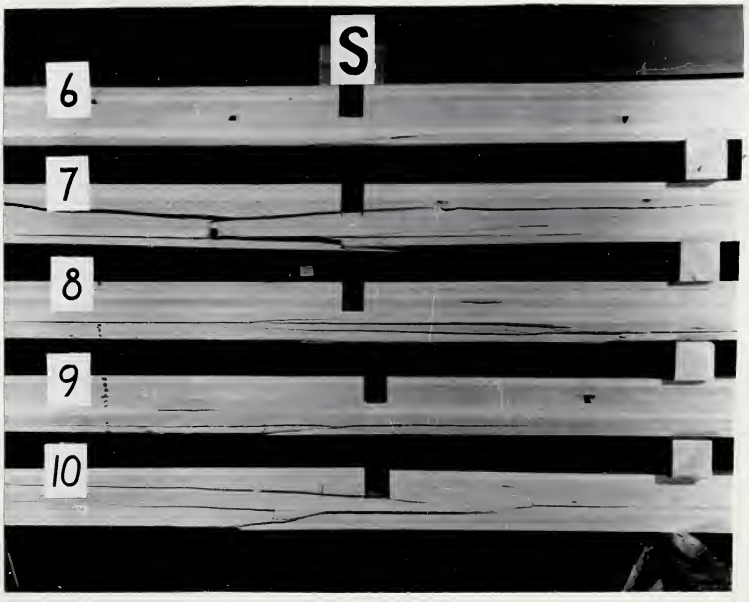


Beams C 21-25

Fig. 18 A (Continued)

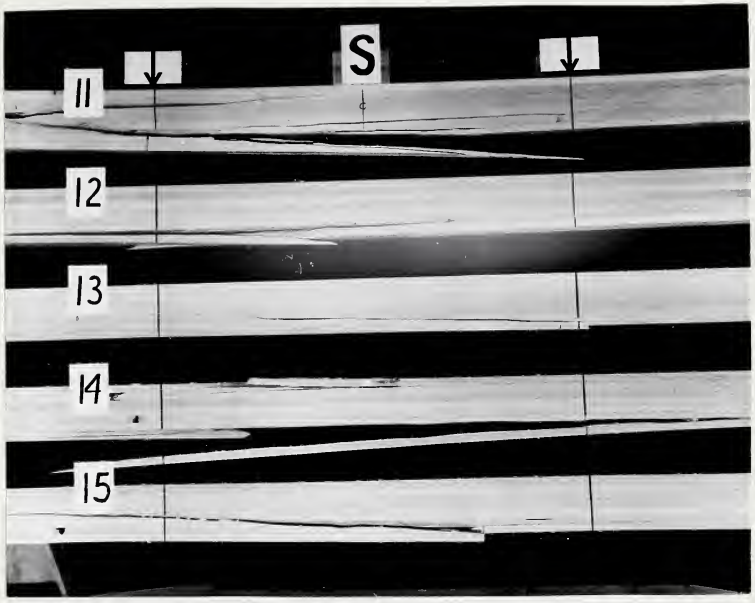


Beams S 1-5

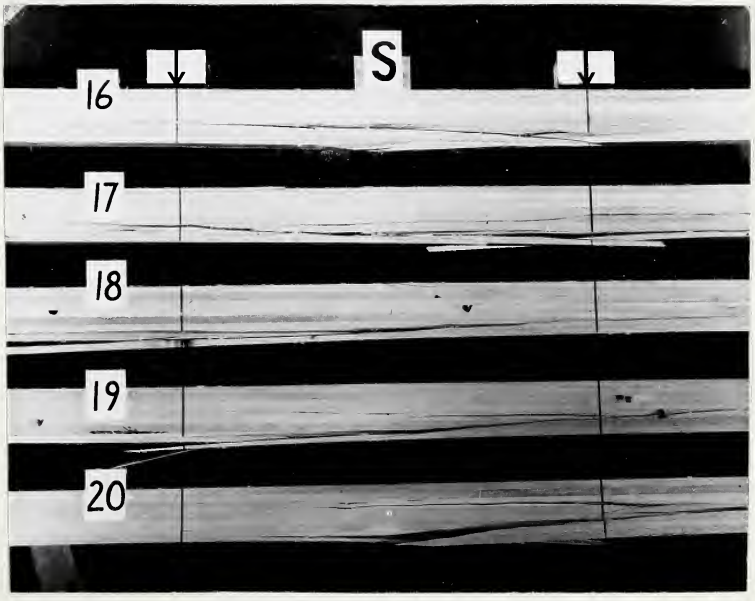


Beams S 6-10

Fig. 18 A (Continued)

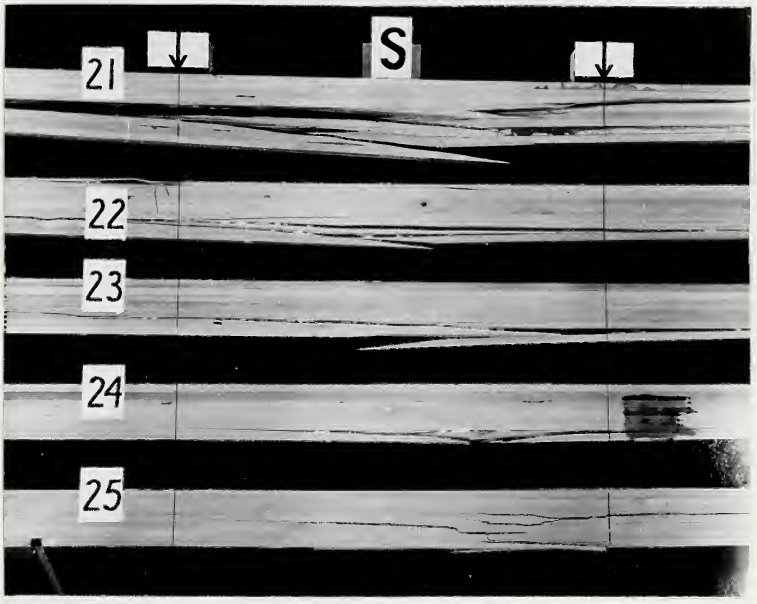


Beams S 11-15



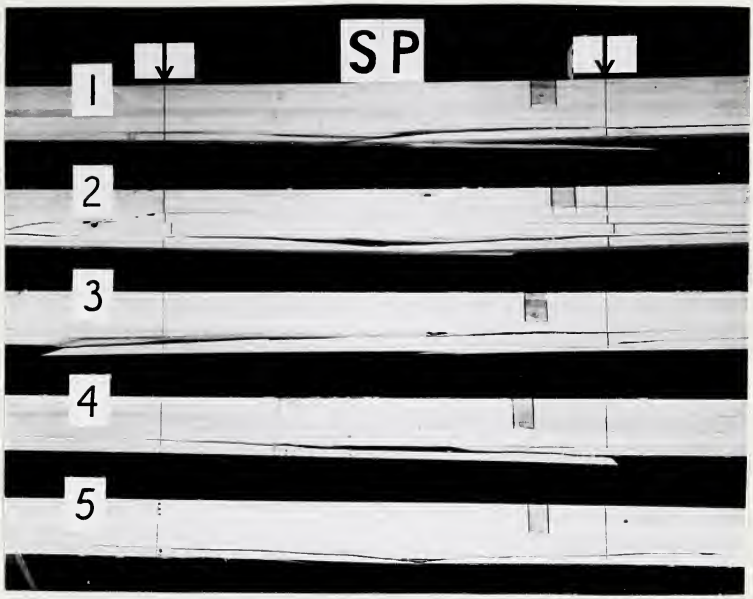
Beams S 16-20

Fig. 18_A (Continued)

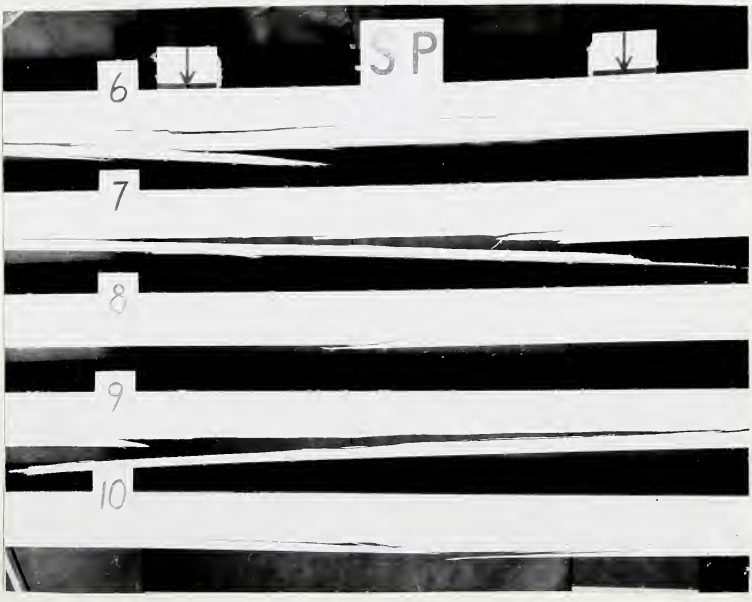


Beams S 21-25

Fig. 18 A (Continued)

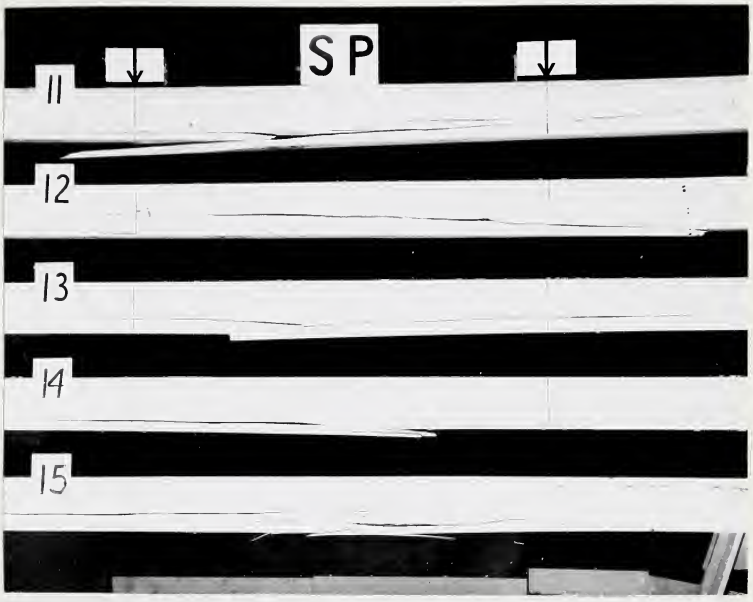


Beams SP 1-5

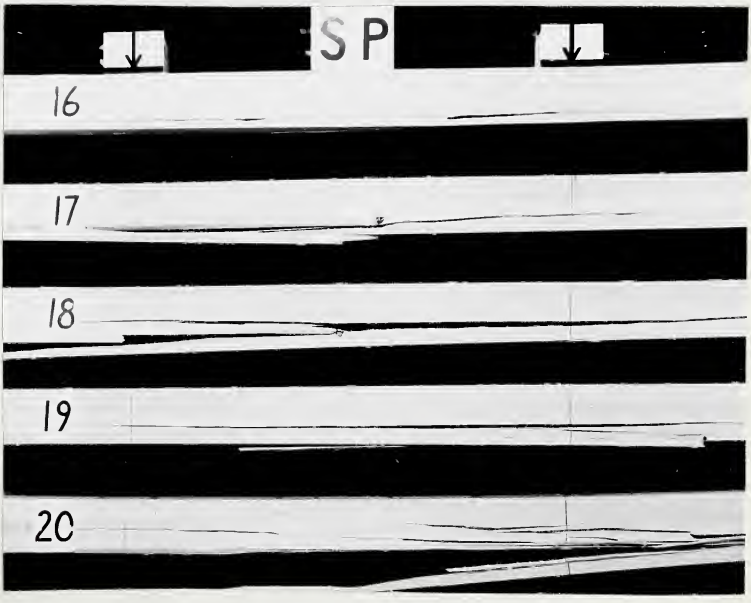


Beams SP 6-10

Fig. 18 A (Continued)

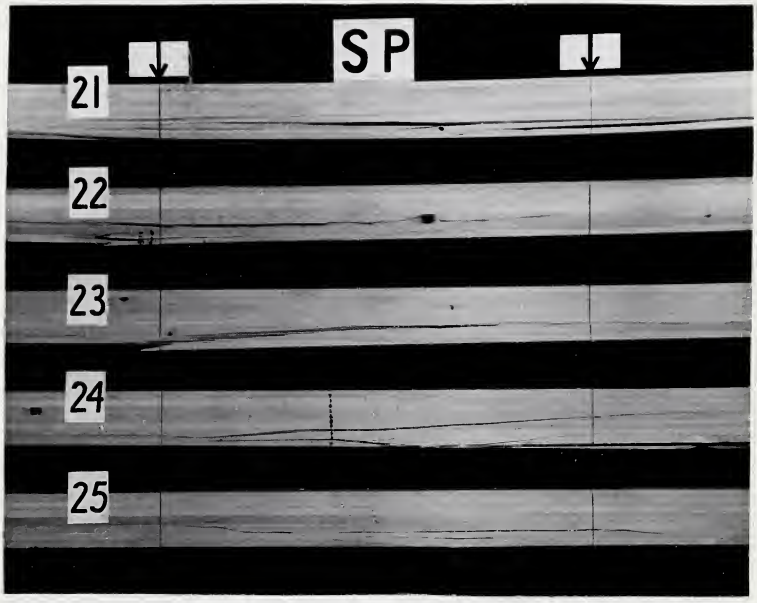


Beams SP 11-15



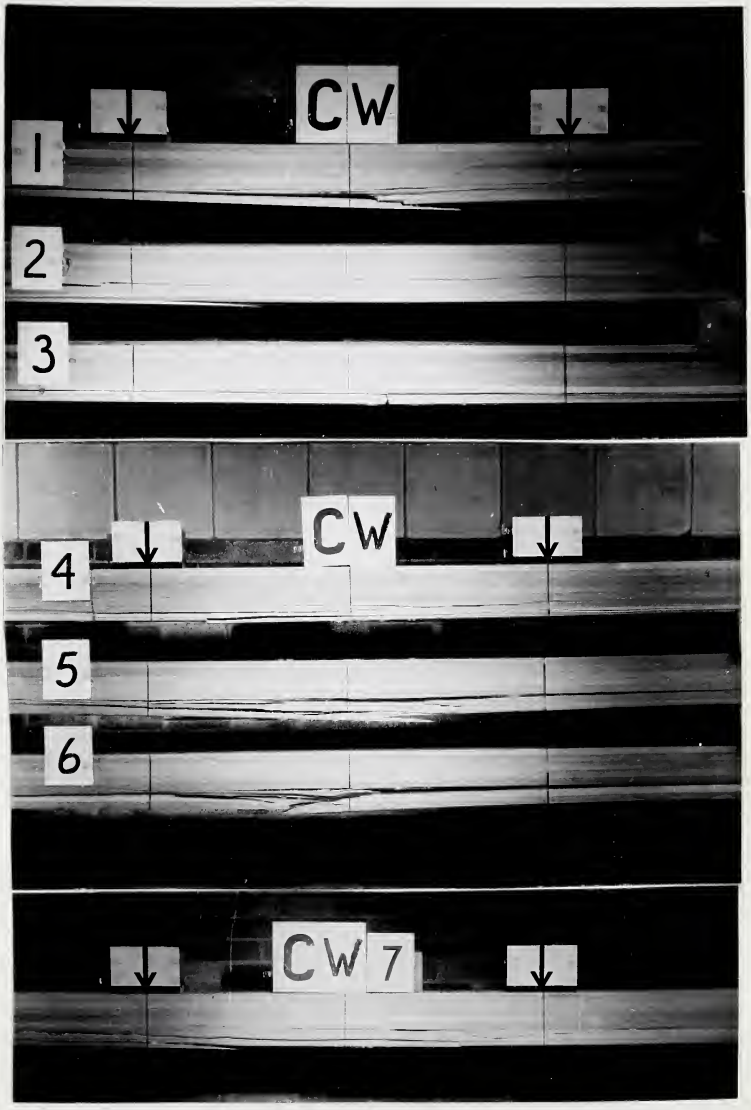
Beams SP 16-20

Fig. 18 A (Continued)



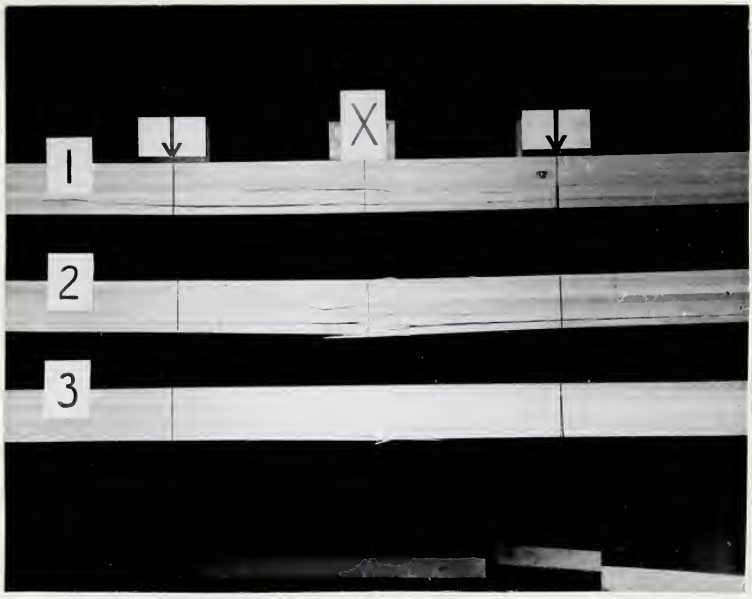
Beams SP 21-25

Fig. 18 A (Continued)

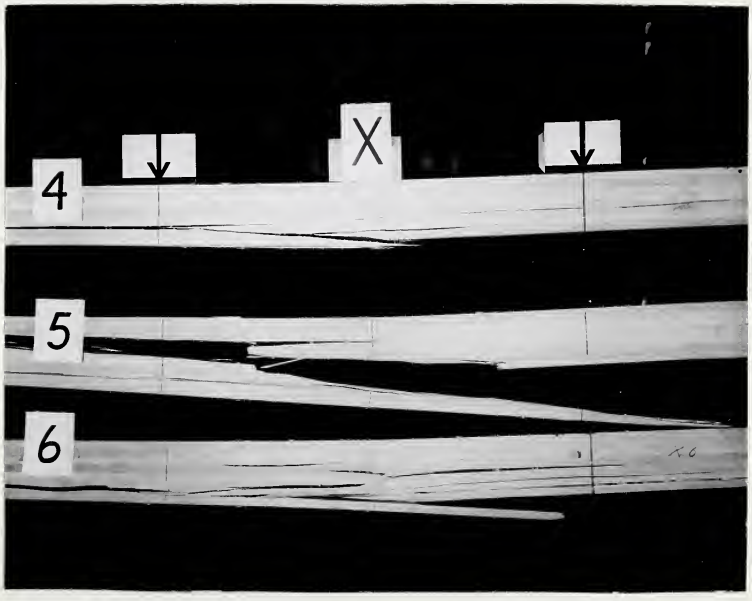


Beams CW 1-7

Fig. 18 B

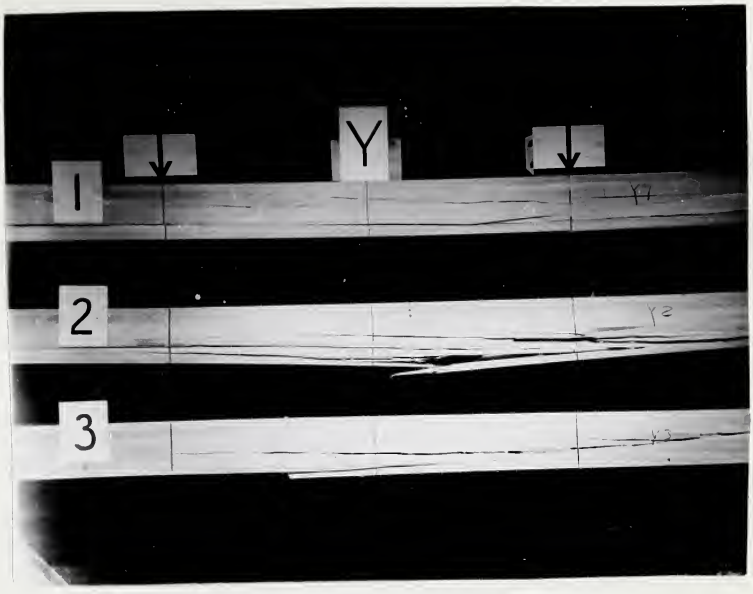


Beams X 1-3

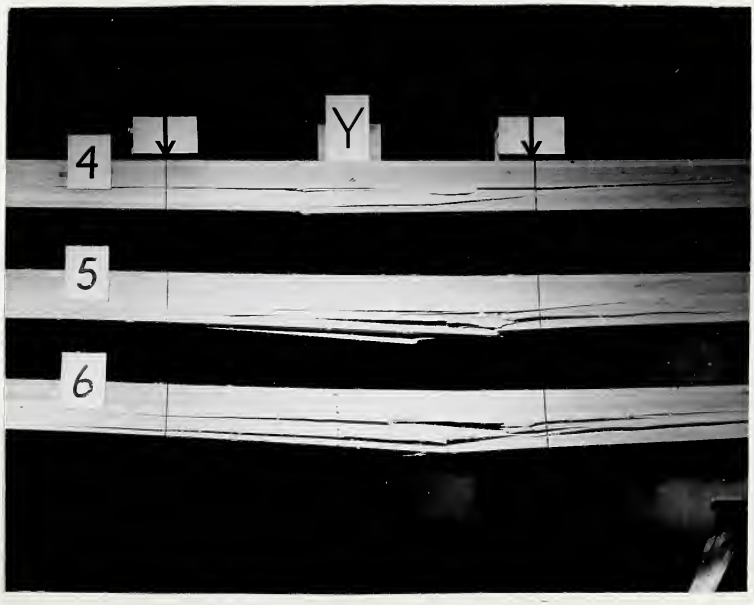


Beams X 4-6

Fig. 18_B (Continued)

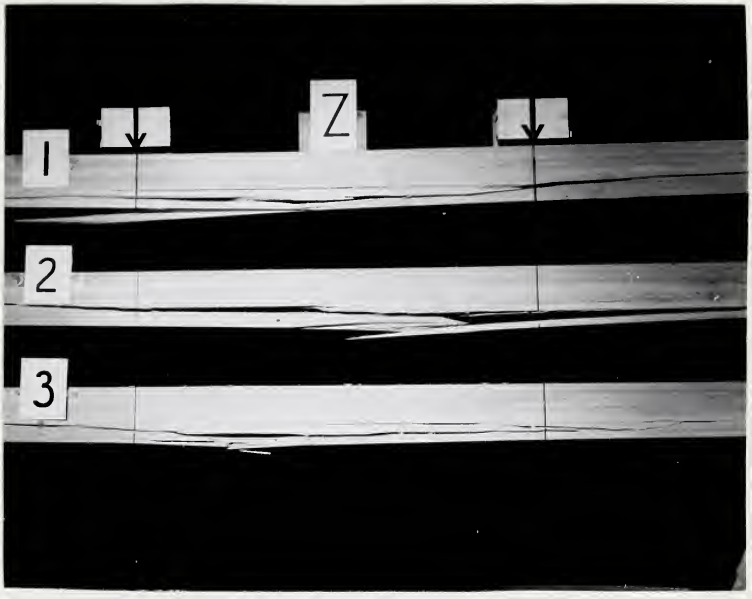


Beams Y 1-3

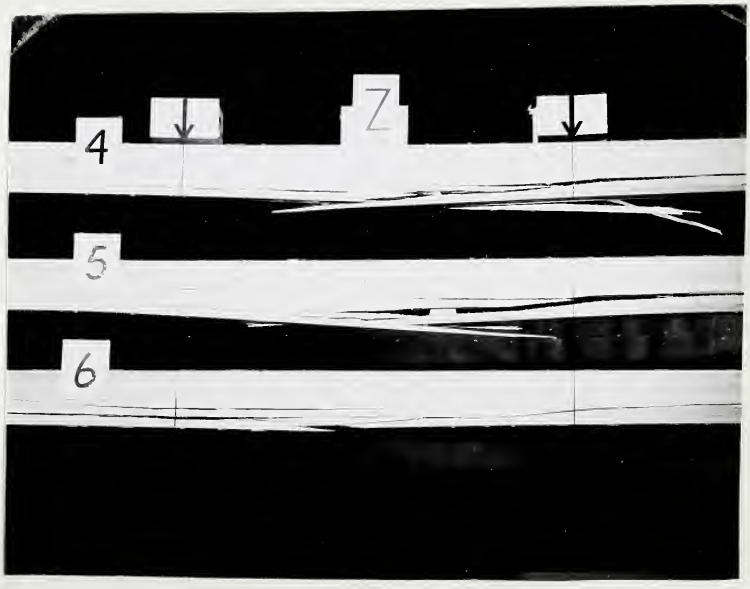


Beams Y 4-6

Fig. 18 B (Continued).

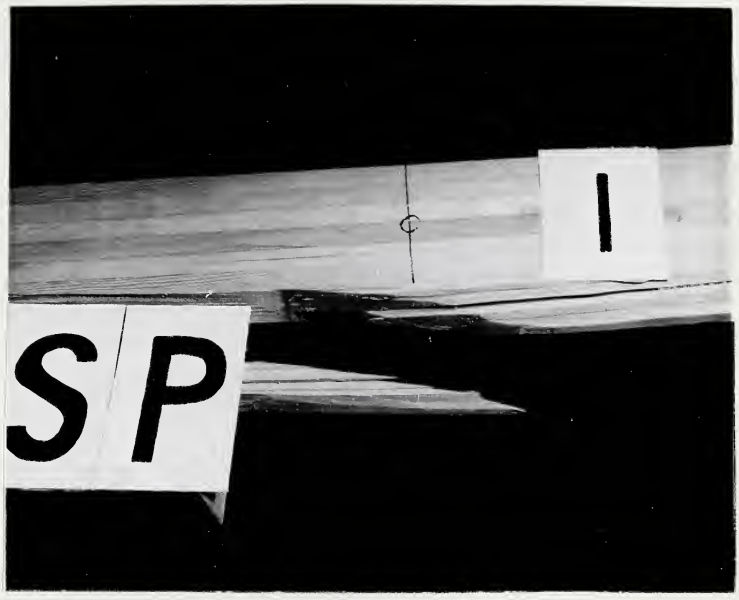


Beams Z 1-3



Beams Z 4-6

Fig. 18 E (Continued)



Scarf Failure

Cross Grain Failure

Fig. 19

Cross Grain Failure

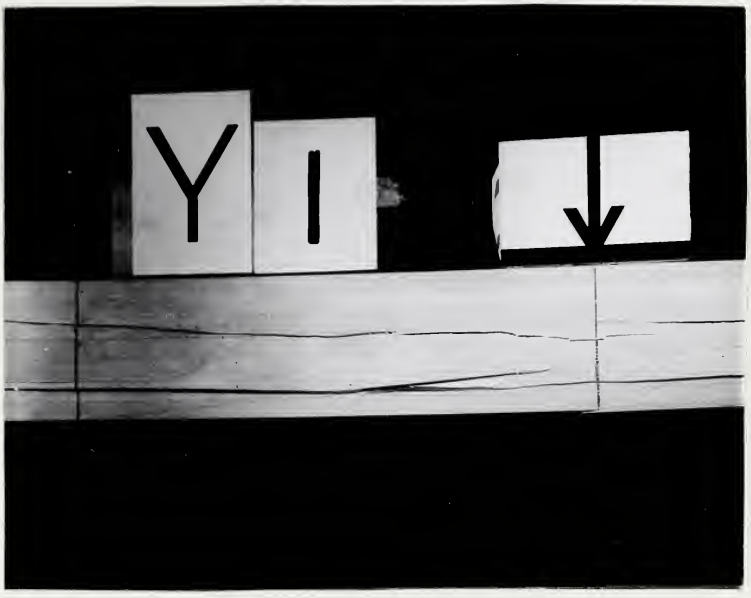
Splintering Tension Failure

Fig. 19 (Continued)

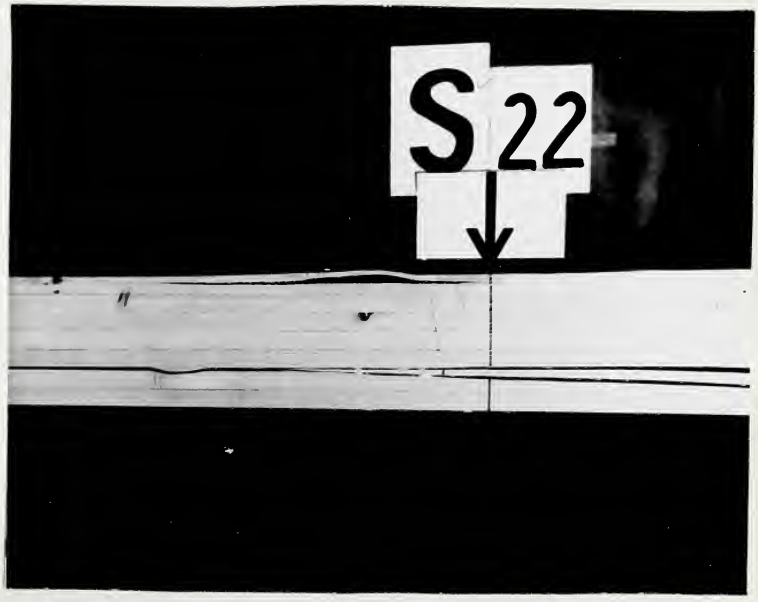
Cross Grain Failure, Bottom View

Transverse Tension Failure

Fig. 19 (Continued)



Scarf Failure in Second Lamination
Bottom Lamination Unfractured



Compression Failure at Pitch Pocket

Fig. 19 (Continued)

DISCUSSION

(A) Considerations Common to All Series:

The material for the beams of groups C, S and SF has been classified by the fabricator as grade D material as defined by the laminating specifications of the Canadian Standards Association (3). On the basis of careful visual inspection there appeared no justification for such a classification. It has been pointed out elsewhere that the material was selected very carefully. The author himself did not detect any cross grain in the material prior to gluing. For ordinary laminating purposes as well as for these tests the lumber definitely had to be classified as grade A material. The following discussion therefore is based on a grade A classification of the lumber for all beams.

Specific Gravity: The results of all test series are tabulated in Tables 2 A and 2 B. Columns 2 and 3 of these tables give the specific gravity and moisture content of the beams. It has already been mentioned that the specific gravity of the beams in the first set varied considerably. The histogram Fig. 3 is a representation of values determined from samples cut from the top of the laminated beams, while Fig. 4 shows values obtained from samples from the bottom of the beams. When the material for the second set of beams was graded according to its specific gravity a similar spread of values was evident. This large spread of values of specific gravity can be seen in the histogram, Fig. 5. No attempt will be made here to explain the various peaks in this histogram. It should be noted however that the same trend was already indicated in the values of the specific gravity of the first set of beams. The wide spread of

values and the various peaks are characteristic of all these histograms. To reduce the adverse effect of the large spread on the strength of the beams, the material for the second set of test beams was therefore grouped according to its specific gravity. The distribution of the specific gravity values in these groups is shown in Table 8.

TABLE 8

Group	Range of Spec. Grav.	Average Spec. Grav.
A	0.59 - 0.65	0.62
B	0.54 - 0.58	0.56
C	0.47 - 0.53	0.50
D	0.66 - 0.71	0.68

This grouping, of course, has nothing to do with the grading systems used for commercial timber. The grouping of the material for the control beams was slightly different and is shown in Table 9.

TABLE 9

Group	Range of Spec. Grav.	Average Spec. Grav.
A	0.58 - 0.60	0.59
B	0.53 - 0.57	0.55
C	0.49 - 0.51	0.51
D	0.67 - 0.72	0.69
E	0.42 - 0.45	0.44

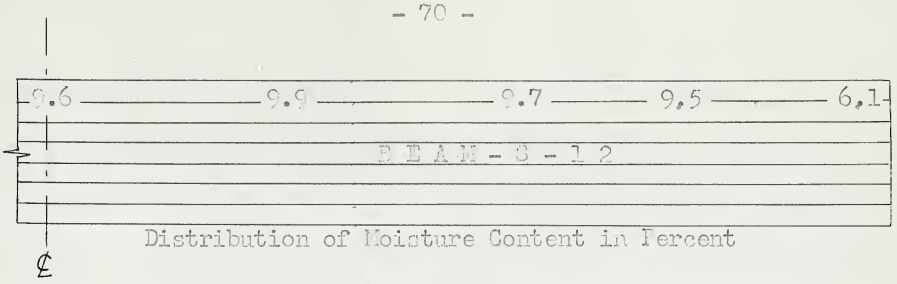
The resulting specific gravity distribution in the layer failing first in the test beam is given in Fig. 8 and Table 6 D. It is obvious that the spread of values has decreased considerably

and that they are packed much closer about the average of 0.5. The group of relatively low values for the control beams corresponds to the lower average specific gravity of group A of the material for these beams.

It has been suggested that the large spread of specific gravity values might be due to a variation in moisture content. This however could not be verified. When the specific gravity values were corrected for moisture content the whole curve merely shifted somewhat towards the origin, but essentially retained its former shape.

Moisture Content: The moisture contents for beams C 1-25 and S 1-20 represent values obtained from one test sample only taken from the centre of the beams. Only one value is given since it became obvious as the tests progressed that the value obtained from the end sample was not representative of the moisture content of the beam. This value was always 4 or 5% less than that obtained from the centre sample. The explanation for this difference of course was that the end sample while still part of the beam had one more surface from which moisture could evaporate than the centre sample. This surface in addition was one perpendicular to the direction of the fibres. This naturally would increase evaporation even further.

To check the distribution of the moisture content in a beam five samples were cut from beam No. S-12 equally spaced between the centre and the end. The moisture content of these samples is given in Fig. 14.



Distribution of Moisture Content in Percent

Fig. 14.

As was suspected, the moisture content of the end sample was sharply reduced while that of the other four samples was fairly uniform. It was then decided to cut the second sample approximately two feet from the end of the beam. The moisture contents reported for all further beams are therefore averages obtained from two samples as indicated above.

Tests in the previous year at the University of Alberta had shown that it takes a long time before the equilibrium moisture content in laminated wood beams is reached. Therefore it was decided not to attempt to obtain the same moisture content in all beams. For this reason the range of values, 8% to 17% is larger than one would expect in a closely controlled test series. However most values are around 10% (Tables 6 A and 6 B) and only a few samples showed the extreme limits given above.

It may be noted that the moisture content of the beams tends to decrease from series C to S and SP (Table 6 A). This corresponds to the order in which these beams were tested. All beams of series C, S and SP arrived at the same time in January. Beams of series C were tested shortly after they arrived in the laboratory. These tests were followed by those of series S, while the SP series was tested last about four weeks after the beams had been manufactured. The one to

three weeks between testing of series C and SF produced a change in the average moisture content from about 13% to approximately 10%. The reason of course was that the equilibrium moisture content was higher for lumber in the plant than for the same material stored in the laboratory.

The moisture content readings of 8 and 10% reported in the Uniform Glulam Certificate (Appendix C) supplied by the fabricator were obtained with an electric-resistance moisture content meter. The reason for the difference between these values and those obtained in the laboratory from small test cubes has not been investigated. It is felt however that the laboratory values are more representative than the moisture content obtained with an electric-resistance meter, since the determination of the moisture content in the laboratory involved the actual weighing of samples in their original condition and after drying.

Types of Failure: Column 4 in Tables 2 A and 2 B gives the maximum deflection that was observed at failure. In some cases this deflection had to be extrapolated since no reading had been taken just prior to failure. Columns 5 and 6 give the first and second failure loads. In most cases the first was the ultimate failure. However in a few cases the beam was still able to support a load even after some portion of the beam had failed. These initial failures were often of a local nature. They occurred usually at a weak point such as a point of grain irregularity. Frequently initial failure was due to cross grain. It was not possible to predict how an initial cross grain failure would develop. Sometimes the beam would continue to fail due to cross grain, in other cases a tension failure at some other section or even a compression failure would

govern the ultimate load carrying capacity of the beam. These ultimate failure loads are recorded in column 6..

The last column in the tables of test results gives a short description of the type of failure encountered. According to the appearance or the location the fractures were grouped into five classes:

(1) Tensile failures

(2) Compression failures

(3) Horizontal shear failures

(4) Cross grain failures

(5) Failure at the joint

The first four of these failure types are described in the ASTM Standards for the Tests for Small Clear Timber Specimen (1). This standard requires that "failure be classified according to the appearance of the fractured surface and the manner in which the failure develops" (See Fig. 13). Failure at the joint implies that either the glue in the joint failed partly or completely or that the wood fibres separated parallel to and very close to the glue line.

These five basic types of failure cannot definitely describe the great variety of possible failures in a non-homogeneous material such as wood. Tensile failures and failures at the joint especially showed considerable variation. Tension failures were transverse, simple or splintering. Deep as well as shallow tension failures at the scarf were observed with percentages of glue failure ranging from 0 to 75%. However since there is no particular value in these finer descriptions for the present investigation they will not be discussed

further. For a discussion of shallow and deep wood failures, as well as transverse, simple and splintering tension failures the reader is referred to theses by Fox (8) and Edlund (5).

(B) Analysis of Series C, S and SP.

Analysis of First Failure Loads: A statistical analysis of the data presented in Tables 2 A and 2 B was prepared by the Canadian Institute of Timber Construction. Results of this analysis are given in a report presented in Appendix A.

The analysis of the data in Table 2 A has been based on first failure loads only. For phase one the report states that "the difference between the average strength of the two scarf joint groups was not found statistically significant. However the planed scarf group might merit a preference on the score of variability." Since cross grain failures were widely distributed in all groups the report "considers it unlikely that the comparison in strength of the two groups of beams was unduly biased by a preponderance of cross grain in one or the other". It is held therefore that "the experiment has not clearly shown, that the planing of the bottom surface has improved the strength of the beam in the case of a beam made with feather-edge scarfs".

The above analysis is based on the mean strengths of groups C, S and SP. This approach assumes that the nature of the failures in each group was such that the strength of the beams for one particular group could be combined to obtain an average strength value for that group. It assumes in particular that the mean strength of groups S and SP is determined entirely by the nature of the scarf

joint. A close examination of the test results however reveals that more than two-thirds of the first failures in groups S and SP occurred not at the scarf, but at a considerable distance away from it. The mean strength of groups S and SP are therefore not characteristic of the strength of a section containing a planed (SP) or unplaned (S) scarf joint.

To obtain a better estimate of the strength of sections containing a scarf-joint, the first failure loads for each type of beam were grouped according to the type of failure observed. The resulting mean stresses together with some statistical information are given in Table 3 A. Failures caused by obvious defects of the beam, like knots or holes, have been omitted from this analysis.

Statistical analysis of the failures at the scarf shows it is highly improbable that the difference of 1520 psi occurred by chance, i.e. the increase in strength of the scarf joint was not accidental but probably due to the planing of the scarf joints. (See Appendix B). It is interesting to note that the failure stress of group SP at the scarf joint is virtually the same as that of the mean failure stress of the control beams.

The observation that only a small number of beams actually failed at the scarf joint suggests, that (a) the glued plain scarf joint can be stronger than the material joined together and (b) the strength within one board can vary considerably. The first statement would imply that failure has to occur at (right adjacent to) the joint. This is substantiated by investigations at the U. S. Forest Products Laboratory, where it has been found that "casein glue produces joints in most of the common species of wood that are equal

to or greater than the strength of the wood itself" (7). The Canadian Standards Association in its Specification 0122-1953 actually requires that glue joint specimen when tested in shear show a minimum of 80% wood failure in order to be representative of an acceptable glue joint.

With regard to the second statement, it should be observed that the average cross grain failure stresses for both the S and SP groups are lower than the stresses for failures at the scarf in the corresponding groups. In the SP group the tensile failure stresses too are smaller than the scarf failure stresses. Only for the tensile failure stresses in the S group is this relation invalid. This higher average failure stress could be due to the small number of specimens in this group and category. These observations substantiate the above two assumptions regarding the nature of the strength of plane scarf joints.

The fallacy of employing the group means for a comparison of the three groups is further indicated by a comparison of the group means of groups S and SP with the scarf failure stresses in the same groups. While the difference in the two values for group S is smaller and can be attributed to chance, it is highly probable that the corresponding difference in the SP group of 1040 psi is a true difference. (Appendix B). Since we have a true difference between the average scarf failure stress and the group mean in group SP, we must conclude that the group mean is not indicative of the strength of the SP group as determined by the strength of the scarf joint.

The large number of cross grain failures in this test series was quite unexpected. The specifications for the material

of the test beams definitely called for straight-grained lumber. Visual inspection of the selected material for the beams did not reveal any cross grain. Nevertheless one-third of all the beams failed in cross-grain. The reason for this apparent contradiction is that there are two types of cross-grain. The first type, so-called diagonal grain, is caused when a board is cut not parallel to the edge of the tree (Fig. 16). This type of cross-grain is easily recognized, since the layers of annual growth do not run parallel to any of the surfaces of the board. The second type of cross-grain is due to an inclination of the individual tracheids to the axis of the tree. This physical condition is called spiral grain. The ASTM standards for the testing of wood (1.) draw specific attention to the fact that this spiral grain is difficult to detect by visual inspection. Since detection by visual means is very unlikely it is therefore quite possible that lumber graded visually as grade A material still may contain spiral grain.

In the present tests the most striking fact is possibly that the highest as well as the lowest average failure stress on the tension side is to be found among those beams failing by cross grain. Since a visual inspection had not disclosed the presence of cross grain it can be assumed that the cross grain failures were due to spiral grain. The physical meaning of spiral grain is discussed elsewhere. The observed slopes of the cross grain failures certainly are not in contradiction with those expected in spiral grain. Preston (15) reported values ranging from 2 to 13 degrees for the slope of the spiral grain. The corresponding values of the tangent, 0.035 to 0.23, do not differ greatly from the slopes of cross grain failures observed in the

present investigation, ranging from 1:4 (0.25) to 1:13 (0.077).

The small difference of 118 psi between the cross grain failure stresses of groups S and SP is not significant. This is consistent with the assumption that these failures are not influenced by the scarf joint. The difference between groups C and S as well as C and SP however cannot be attributed to chance on the basis of a t-test. Why this should be the case is far from obvious. All these cross grain failures started a considerable distance away from the scarf and therefore could not have been initiated by a stress concentration at the scarf joint. It might be that the small number of such failures in the C group influenced the corresponding mean value unduly. Suspicious also is the high moisture content in group C as compared with that in groups S and SP (See Table 6 A). However since not enough evidence was available no correlation between these data has been attempted.

While no explanation can be given of the large variation of cross grain failure stresses these data should at least be regarded as a warning that the strength reducing effect of spiral grain can be considerably greater than that of a plane scarf joint.

In the first group of beams only three specimens failed in compression (Table 3 A). The high average failure stress, the highest of all mean stresses of C,S or SP type beams is not inconsistent with the flexural theory advanced by Bach and Baumann (2). The fact that these beams failed in compression does not necessarily mean that the compression strength of the wood in these beams was less than in the other beams, but rather that the tensile strength of the bottom lamination was greater than in the rest of the

specimens (See Fig. 15). This behaviour is analogous to that of a reinforced concrete beam, which will fail in compression when over-reinforced on the tension side.

Two of the control beams failed in horizontal shear. The average failure stress of 300 psi computed from $v = \frac{3V}{2bd}$ appears to be low. Reece (16) reports a maximum shear strength parallel to the grain of 1100 psi on small clear specimens of Douglas Fir. Since this failure shear stress of 300 psi is higher than the shear stress computed for those beams of this test series that failed in some other way, it cannot be said how many more specimens had an ultimate shear strength of this magnitude. Longitudinal shear failures appeared to occur along a smooth surface located entirely in one layer of springwood. Freas (19) reports the same type of shear failure in other Douglas Fir beams that also showed low shear strength. Freas attributes this kind of shear failure to a layer of weak cells located in the material first formed at the beginning of the growing season. Although no microscopic examination of the failure surface has been made in the present test series, the appearance of the failure surfaces suggests the same explanation for the low shear strengths reported in the present investigation.

Ultimate Failures: It has been mentioned earlier that some beams were able to sustain increased load after initial failure had occurred. Edlund (5) reports similar observations on glulam beams with hooked scarf joints. He observed that, after failure of the bottom lamination had occurred, the remaining section was still able to support a considerable load. As the load was increased and the beam deflected further, the bottom lamination began to peel off

along the horizontal glue line, until the remaining section finally ruptured. Such behaviour was observed in only a few instances in the present beam tests. Where the beam was able to sustain further load after rupture of the bottom lamination, failure on the tension side of the beam continued in most cases in a horizontal direction in the wood and not in the glue. Final failure at times was a continuation of the original failure, at other times it occurred at a different location.

These secondary failure loads as well as the failure loads for beams failing entirely at first failure have been grouped together as ultimate failure loads. The group means of the corresponding ultimate failure stresses are given in Table 4 B. Although an attempt had been made to classify the rupture loads according to the type of failure observed, only mean strength values for each beam type have been calculated. The behaviour of a beam, after first failure had occurred, was so erratic, that to attempt any further refinement beyond the computation of group means seemed unjustified.

Statistical analysis of the group means of the ultimate failure stresses indicates a real difference between these means. This finding agrees with the analysis of first failure stresses at the scarf joint. However it is doubtful if this analysis of ultimate failure stresses is of much value. As has already been pointed out, the overall group means are influenced not only by the strength of the scarf joint, but also by other factors. The validity of a comparison of overall group means therefore is questionable.

Stress Ratios: To provide a better comparison of the mean initial failure stresses, a number of stress ratios have been computed (Table 5 A). The mean strength of beams failing by cross grain has been compared with the mean tensile strength of beams in the respective groups. These strength ratios range from 1.0 for the control beams to 0.76 for the S group, with the value of 0.85 for the SP group falling between the two extremes. A proper analysis of the flexural strength of beams containing cross grain should certainly take into account the slope of the grain and that of the failure line. Some of this information is given in the tables of results (Tables 2 A and 2 B). However such an investigation is beyond the scope of this thesis and therefore has been omitted. It is sufficient here to note that the reduction of strength due to spiral grain can be larger than that due to the slope of the scarf joint. If the group mean strength for the control beam is chosen as a standard of comparison, the resulting strength ratios would be even smaller.

Failures at the scarf have been compared with the mean strength of the control beams. For the S group the resulting strength ratio S/C = 0.82 is smaller than the strength ratio for a 1:12 plain scarf joint of 0.9 recommended by the Canadian Standards Association (See Table 1). On the other hand for the SF group a value of SF/C = 1.0 has been obtained. A t-test of the very small difference between mean failure stress at the scarf (SF) and group mean strength of the control beams (C) confirms that this small difference is due to chance.

Investigations into the effect of plane scarf joints on the flexural strength of laminated beams have been done previously by the U. S. Forests Products Laboratory (18). For beams with 8, 11 and 17 laminations containing a plain scarf joint with a slope of 1:12 in the bottom lamination, strength ratios of 0.91, 0.87 and 0.92 respectively are reported representing averages from three specimens. The value presented in this thesis, S/C=0.82, indicates that those strength ratios (18) are perhaps too liberal.

A similar observation with regard to scarf joints containing end steps has already been reported by Edlund (5) and Fox (8). Their tests indicated that the actual strength ratios for scarf joints containing end steps could be as low as 72% of those calculated from the provisions of the National Building Code of Canada or the Canadian Standards Association.

In an attempt to analyse the factors contributing to the lowered value of the strength ratio Fox and Edlund make a distinction between slope factor and grain alignment factor. Such a differentiation cannot be justified on the basis of the definition of the slope factors proposed in report No. 1622 (11).

When discussing the results of tension tests on matched scarf joints in Douglas Fir report 1622 states:

> "Most of the failures for specimens with scarf joints of a slope of 1:20 failed away from the joint, but still the average strength ratio of specimens with a scarf joint and without was below 100%, indicating that even at very gradual slopes of scarf some slight decrease in strength can be expected. This may possibly be explained as follows: In the process of end-joining two pieces of wood the summerwood

portion of the annual growth layers, which are high in strength and the spring wood portions which are low in strength, are not well aligned. Thus parts of the summerwood may be end-joined to parts of the spring wood and the resulting strength could conceivably be less than for uncut pieces. The number of failures at joints increased with an increase in the slope of the scarf and for a slope of 1:3 practically all failures occurred in the glue joint."

In a later report from the same source (18) the following statements are made with regard to the strength of scarf joints:

"In actual fabrication summerwood will be joined to springwood over part of the area of the joint and the strength of that part will be dependent on the strength of the weaker springwood, so that, even with the best technique in fitting and gluing, lowered efficiency is to be expected.

Considering the range of efficiencies demonstrated in tension tests of jointed specimens and of the probable lowered strength of jointed laminations made generally as compared with those tested, it appears desirable to use lower efficiencies than the average values found in test."

Table (1) shows the observed and the recommended efficiencies of plain scarf joints as reported in report No. R 1607 of the Forest Products Laboratory (18). If for purposes of comparison a modification factor for a particular beam has to be calculated on the basis of the National Building Code of Canada, strict adherence to the code should be required. In this case the National Building

Code requires in section 4.3.4.4. that the area of the end step be considered as a butt joint, e.g. not transmitting any stresses in either tension or compression. In the case of Edlunds beams loaded in bending this requires the computation of a net modulus of inertia ($I_{net} = 1(5.435 - 0.130)^3/12 = 12.456$). The gross moment of inertia for his beams is $I_g = b5.435^3/12 = 13.4b$. The modification factor therefore will be 12.45/ 13.4 = 0.93. Since this modification factor and the strength reducing factor due to slope are cumulative, the overall expected efficiency would be 0.90 x 0.93 = 0.84. In any comparison between an actual strength ratio and a value based on the National Building Code this value of 0.84 must be used. It can then be concluded, that the difference between an actual strength ratio of 0.61 and a calculated one of 0.84 is due to inadequacy of the code, primarily because the code neglects the possibility of stress concentrations at the end step of the scarf joint. It is important to note that the ratio of 0.61/0.84 = 0.725 between actual and calculated stress ratio is even larger than estimated by Edlund.

In conclusion it should be stated that the modification factor proposed in the National Building Code for a scarf slope of 1:12 appears too high. For scarfs with end steps, stress concentrations at the tips of the scarf cause a considerable reduction of the strength. Allowance for this stress concentration should be made in the code. For plain scarf joints the present tests indicate lower efficiencies than were obtained by the U. S. Forest Products Laboratory. When discussing the magnitude of the reduction in strength due to a 1:12 scarf slope the allowable design stresses

for a grade A material should be considered as well. The writer agrees with the assumption made by the Canadian Standards Association that for any material the effect of a 1:12 plain scarf joint need not be considered when establishing a working stress. Considering the large basic stress for Douglas Fir recommended by the Canadian Standards Association (3190 psi) and the low initial mean failure stress at the scarf (6770 psi) and due to spiral grain (6250 psi) obtained in this test series it is questionable if a reduction of the basic stress by 10% is sufficient for grade A material.

For design purposes Freas and Selbo (9) propose that the strength reducing effect of the slope of cross grain be combined with that of the slope of the scarf joint. Again a distinction between spiral grain and diagonal grain should be made. Fig. 16 shows the possible cross grain failures in edge-grained and in flat grained lumber. Since end-grain gluing is more difficult than side-grain gluing, scarfs cut across the general direction of the grain showing more end-grain, will be relatively weak (9). If we consider spiral grain this situation will be much more pronounced in an edge-grained board (Fig. 16a) than in a flat-grained piece (Fig. 16b). On the other hand for diagonal grain the situation is reversed. Here flat grained boards (Fig. 16c) will show more end-grain than edge-grained boards (Fig. 16d) when scarfed across the grain. Consequently for diagonal grain flat grained boards are less desirable than edge grained boards.

As has been pointed out elsewhere, diagonal grain can be readily identified. It is therefore quite obvious when a factor

for cross grain has to be applied. On the other hand, spiral grain is difficult to detect by ordinary means. To avoid the cumulative effect of spiral grain and scarf slope it therefore seems to be of advantage to use flat-grained in preference to edge grained material. The validity of this reasoning is indicated by results of the present beam test series. It was observed in a few instances that spiral grained and flat grained scarfed laminations failed along the direction of the spiral grain through the scarf, without failure at the scarf itself.

(C) Analysis of Series X, Y, Z and CW

First Failures: Test results of series X, Y, Z and CW are given in Table 2 B. A statistical analysis of the results of the second series of tests as prepared by the Forest Products Laboratory of Canada is presented in Appendix A. In contrast to the analysis of the first series of beam tests, where the calculations were based on first failure loads, the analysis of the X, Y, Z and CW series is based on ultimate failure loads. No reason for this different approach is given in the Forest Products Laboratory report.

The results of an independent analysis by the author are given in Tables 3 B and 4 B. The small number of specimens in each group did not justify a classification of the results according to types of failure. Therefore only group means are given. A t-test of the differences between mean initial failure stresses indicates that only the differences of 150 psi and 750 psi between groups X-Y and Z-CW respectively are likely to have occurred by chance. All other differences show a large probability of being real. An

analysis of the ultimate failure stresses gives a slightly different result. Differences between ultimate failure stresses of series X, Y and Z appear to have occurred by chance, while the higher mean strength of the control beams appears to be not accidental.

Conspicuous is the relatively large number of compression failures in these tests. In most cases these compression failures occurred first at a scarf joint. There are not enough data to substantiate a claim that these scarf joints in the top lamination are locations of reduced strength. However the test results certainly indicate that this possibility ought to be investigated more thoroughly.

Tension as well as cross-grain failures were observed. Initial failure usually did not occur at a scarf joint. It is therefore doubtful that the statistical analysis, showing a real difference between most scarf-jointed beam types and control specimens gives a proper evaluation of the tests. The absence of initial failures at the scarf makes it much more likely that the plain scarf joints do not influence the initial strength of the beams at all. The same conclusion was already indicated by the results of the first series of tests, where about two-thirds of all initial failures occurred away from the scarf-joint.

Ultimate Failures: The ultimate failures showed a considerably larger percentage of failures at the scarf. As loading of the beams was continued after initial failure, the initial crack, in some cases, continued to open up gradually. At ultimate failure this crack usually would advance suddenly for some distance

through the beam till the direction of the crack was blocked by a scarf joint. Then the direction of the failure would change and continue along the scarf joint. This was especially noticeable in the Y-series, although a similar behaviour was observed in some beams of the Z-series. Beams that failed initially in compression, in general failed ultimately in tension along the scarf joint.

A statistical analysis indicates that the difference between the mean ultimate strength values of series X, Y and Z is due to chance. On the other hand the difference in strength between beams containing scarf-joints and control beams has a large probability of being real. The 24-t spacing for scarf joints required by the Canadian Standards Association (3) therefore seems to be too severe a restriction on the spacing of scarf joints. This view is strengthened by the fact that only a small number of beams initially failed at the scarf joint. Considering that the 24-t spacing has been set rather arbitrarily (9) a review of this requirement seems to be indicated.

Stress Ratios: The stress ratios for the initial mean failure stresses range from 0.80 to 0.94. This range of values is similar to that found in the first series of tests. The lower limit of these values is somewhat low as compared with a strength factor of 0.90 required by the Canadian Standards Association.

Interesting, if only of a qualitative nature, is the test result of beam CY-7. This beam was manufactured from material of low specific gravity. The ultimate load for this beam was considerably lower than the mean strength of any other group.

This result is in agreement with the findings of other investigators (18). Various equations have been proposed to express the rupture strength of wood in terms of its specific gravity (6, 18). However these equations differ considerably, probably due to the large variability of the strength of wood of even one particular specific gravity. Therefore in this discussion only the trend to reduced strength with a decrease in specific gravity has been indicated.

(D) Moduli of Elasticity of All Series

Moduli of Elasticity have been computed from the initial tangent slope of the load-deflection curves (Fig. 17 A and B). The mean value of the modulus of elasticity of each group together with the standard deviation and the coefficient of variability is given in Tables 7 A and 7 B. On the tacit assumption that the modulus of elasticity is not significantly affected by the type of failure within one group only mean group values have been computed. A t-test of the difference in the moduli of elasticity between series C, S, and SP shows that these differences can be attributed to chance. Similarly for series CW, X, Y and Z no significant difference between the respective mean values was apparent.

The moduli of elasticity presented in Tables 7 A and 7 B are relatively high. Commonly a range from 1.64 x 10^6 to 1.95 x 10^6 psi for the modulus of elasticity of Douglas Fir is assumed (6, 12). On the other hand the coefficients of variability are low, compared with a value of 22% commonly encountered (6). The mean group values therefore give a reasonable indication of the moduli of elasticity

of the beams tested.

One factor contributing to the high modulus of elasticity was found in the testing arrangement. As has been explained elsewhere in this thesis the test beams were supported by plates hinged to fixed supports. This arrangement prevented free lateral movement of the test beam, when it was loaded. As a test beam was loaded frictional forces were set up between the beam and the plates supporting the beam. These lateral forces would prevent extension of the underside of the beam, till reaction due to the frictional restraint exceeded the frictional resistance at the supports. The beam would then suddenly slide across the supporting plate with a noticeable thud for a short distance till the bottom fibres had elongated sufficiently. This sudden lateral movement would be repeated every time the frictional resistance was exceeded by the reaction caused by the lateral restraint.

Such horizontal reactions cause a uniform bending moment along the beam, opposite in direction to the moment caused by the vertical loads. This results in smaller deflection than would be obtained, if the lateral reactions were not present. When calculating the modulus of elasticity from the load-deflection curve for the observed deflection at the centre of the beam, a higher modulus of elasticity will result than under normal test conditions, e.g. free lateral movement. Calculations indicate that the increase (due to frictional resistance at the supports) in the apparent modulus of elasticity is approximately 4 to 5% of the value obtained by considering the effect of the lateral restraint. (See Appendix D).

The above analysis does not completely explain the relative high modulus of elasticity computed for this series of beam tests. However a variability in the modulus of elasticity of up to 22% has been reported (6) for trees from different localities. The moduli of elasticity presented here, although high, are therefore within normal limits.

Considering the moduli of elasticity of the second group of tests (X, Y, Z and CW), it is worthwhile to note the decrease in the coefficients of variability as compared with those for the C,S and SP series. This is a reflection of the more careful selection of material for these beams. The observation that the modulus of elasticity decreases with a decrease in specific gravity of the wood (6) is confirmed by the test results from beam CWa. Since only one beam of low specific gravity was tested, the results of Table 7 do not lend themselves to a numerical analysis of the relationship between modulus of elasticity and specific gravity. However the trend of decreasing moduli with a decrease in specific gravity certainly is indicated.

In their publication "Fabrication and Design of Glued Laminated Wood Structural Members" Freas and Selbo report that the modulus of elasticity of Glulam beams appears to be uneffected by the scarf-joint spacing (9). This observation, too, is confirmed by the present investigation. A comparison of the respective moduli of groups X, Y and Z does not show any significant difference. In addition it can be said that even the modulus of elasticity of the unscarfed laminated beams does not differ substantially from that of the beams containing scarf joints. This is true for both

groups of tests, as indicated by a t-test of the difference between the various moduli of elasticity.

CONCLUSIONS

The conclusions presented in the following paragraphs pertain to glulam beams of Douglas fir containing one or more plain scarf joints with a slope of 1:12. The term "strength" is used to indicate the flexural strength of a glulam beam just before initial failure occurs.

On the basis of the data presented in this thesis the following conclusions may be made:

1. In glulam beams containing plain scarf joints in the outer lamination, where the wood is as strong or stronger than the scarf joint, average failure stresses as low as 82% of those of beams with continuous laminations can be expected. This is considerably less than permitted by the Canadian Standards Association.

2. Planing of the bottom lamination containing a plain scarf joint can produce a marked improvement of the strength of the scarf joint. In this test series planed beams failing at the scarf joint were as strong as beams with continuous laminations.

3. A variation in scarf joint spacing has no apparent effect on the flexural strength of glulam beams.

4. Plain scarf joints in the top lamination tend to be weaker in compression than the material adjacent on either side.

5. Frequently the strength of glulam beams containing plain scarf joints, planed or unplaned, is not determined by the strength of the scarf joint but rather by that of the wood itself. Group mean strength from tests of glulam beams containing plain scarf joints are therefore not indicative of the strength of such scarf joints, since failure often will occur at some distance from

the joint.

6. Spiral grain can reduce the strength of a beam considerably below that determined by a plain scarf joint.

7. The longitudinal shear strength in Douglas Fir beams is sometimes determined entirely by the presence of one layer of particularly weak cells. However the corresponding shear failure stresses computed for the present tests were still about twice as large as the longitudinal shear stresses permitted by the National Building Code of Canada (12). The shear stresses allowed by the code can therefore be considered as adequate.

8. The ability of some glulam beams to sustain an increase in load after an initial failure has occurred is very unpredictable. Computations of strength ratios should therefore always be based on first failure loads.

9. Lumber selected according to CSA-O122-1953 can show a wide variation in specific gravity. To eliminate a variation in strength of test specimens due to the spread of specific gravity values a grouping of the material according to its specific gravity is desirable. Closer control of test conditions then is possible.

BIBLIOGRAPHY

(1) American Society for Testing Materials.

1952 Standard Methods for Testing Small Clear Specimens of Timber.

Amer. Soc. Testing Materials, Standard D. 143-52 Pt. 4.

(2) Bach, C. and Baumann, R.

1924. Elastizität und Festigkeit.

Julius Springer, Berlin.

(3) Canadian Standards Association.

Specification For Glued-Laminated Timber Construction.

O122 - 1953.

(4) Deutsche Normen

1947. Holzbauwerke. DIN 1052.

(5) Edlund, B.C.

1957. A Study of Some Factors Affecting The Action of Hook Scarf Joints in Laminated Wood Beams.

Thesis, University of Alberta.

(6) Forest Products Laboratory,

1955. Wood Handbook. U. S. Dept. Agr.

(7) Forest Products Laboratory,

1956. Casein Glues: Their Manufacture, Preparation and Application.

U. S. Forest Products Lab. Report No. D 280.

(8) Fox, S. P.

1956. An Investigation Into The Effects of Certain Variables in Scarf-Jointed Timber Laminations.

Thesis, University of Toronto.

(9) Freas, A. D., and Selbo, M. L.

1954. Fabrication and Design of Glued Laminated Wood Structural Members. U. S. Forest Prod. Lab. Bulletin No. 1069.

(10) Ketchum, M.

1949. Big Timbers from Small Sticks.

Engineering News, Vol. 143, pp. 214-216, S 1.

(11) Luxford, R. F. and Krone, R. M.

1953. End Joints of Various Types in Douglas-Fir and White Oak Compared For Strength. U. S. Forest Prod. Lab. Report No. 1622.

(12) National Research Council, Canada.

1953. National Building Code of Canada.

Section 4.3. Wood.

(13) National Lumber Manufacturers Association.

1955. National Design Specification For Stress-Grade Lumber and its Fastenings.

National Lumber Manufacturers Assoc., Washington.

(14) Northcott, P. L.

1957. Is Spiral Grain The Normal Growth Pattern?

The Forestry Chronicle. Vol. 33, No. 4.

(15) Preston, R. D.,

1949. Spiral Structure and Spiral Growth

Forestry, Vol. XXIII, No. 1.

(16) Reece, P. C.

1949. The Design Of Timber Structures.

E. and F. N. Spon Ltd., London.

(17) Van Dyke, J. C.

1956. Recent Developments in Engineered Timber Construction.

American Soc. of Mechanical Eng. Paper No. 56-A-136.

(18) Wilson, T. R. C. and Cottingham, W. S.

1952. Tests of Glued Laminated Wood Beams and Columns and

Development of Principles of Design.

U. S. Forest Prod. Lab. Report No. 1687.

(19) Freas, A. D.

1950. Studies of the Strength of Glued Laminated Wood

Construction.

ASTM Bulletin No. 170, December 1950.

APPENDIX A

ANALYSIS OF DATA

FOR

CANADIAN INSTITUTE OF TIMBER CONSTRUCTION

UNIVERSITY OF ALBERTA BEAM TEST - 1957

BY

OTTAWA LABORATORY

FOREST PRODUCTS LABORATORY OF CANADA

Purpose of Test

Phase 1

To compare the strength of a feather-edged plain scarf joint beam with the strength of the same type planed after manufacture.

To determine the efficiency of the two beam types in relation to that of unscarfed beams assembled from the same material.

To estimate the unit strength of a Douglas fir laminated beam with a feather-edge plain scarf joint.

Phase 2

To explore the effect of certain spacing arrangements:
(a) Stacked scarfs
(b) Scarfs in alignment
(c) The presently specified "24-t" arrangement.

Material

	Type of Beam	No. of Specimens
Phase 1:	Laminated - no scarf	25
	" - feather-edged plain scarf	25
	- " " " " planed after manufacture	25
Phase 2:	Laminated - no scarf	6
	" - stacked scarfs	6
	" - aligned scarfs	6
	" - "24-t" scarfs arrangement	6

Analysis of Test Data
Phase 1:

Strength of a Plain Scarf Joint

Data from Static Bending Test

Statistic	Controls	Plain Scarf	Plain Scarf-planed
N	24	23	23
$\bar{x}$ *	8400	6730	7240
S	1500	2087	1277
V	17.9	31.0	17.6
$S_{\bar{x}}$	306	435	266

1. The difference of 510 p.s.i. between the average strength of the two scarf joint groups was not found statistically significant. However, the planed scarf group might merit a preference on the score of variability.

It is noticeable that six beams in the unplaned group fell below the 5,000 p.s.i. mark. Four of these were cross-grain failures. A similar number of low strength pieces did not occur in the planed group. The reason for this is not clear. It would be caused by chance or it could be that some poor quality pieces were improved by planing. It is not possible to say with the evidence at hand. However, cross-grain failures were widely distributed among the test pieces and it is considered unlikely that the comparison in strength of the two groups of beams was unduly biased by a preponderance of cross-grain in one or the other.

The experiment has not clearly shown, therefore, that the planing of the bottom surface has improved the strength of the beam in the case of a beam made with feather-edge scarfs. This would indicate that the reduction in strength caused by slight irregularities at the tip of a feather-edge scarf is so small as to leave little room for improvement by planing, and does not in any way refute the observation of previous bending tests that planing can have a pronounced beneficial effect in scarf joints with thick end steps and deep notches.

* Average Modulus of Rupture, p.s.i.

2. The efficiencies of the beam types are as follows:

Feather-edged plain scarf joints	80%
" " " " planed	86%

3. The average strength of Douglas fir laminated beams, estimated with 95% confidence intervals about the mean would be as follows:

Without scarfs	8400 ± 630 p.s.i.
With feather-edged plain scarf	6730 ± 900 p.s.i.
With feather-edged plain scarf planed after manufacture	7240 ± 550 p.s.i.

Phase 2:

Effect of Spacing Arrangements

Data from Static Bending Test

Statistic	Controls	Stacked Scarfs	Scarfs in Alignment	"24-t" Arrangement
N	6	6	6	6
$\bar{X}$	12520	10510	10720	10830
S	1478	258	1458	558
V	11,8	2.5	13.6	5.2
$\bar{Sx}$	603	105	595	228

1. Analysis of variance comparison shows no significance in the difference of 320 p.s.i. and 110 p.s.i. in the strength of the presently specified "24-t" arrangement and that of the other two scarf joint groups.

2. The efficiency of the combined group of 18 scarf joint beams is 85.4%.

3. The smple size was not planned to be large enough for estimating strength but was intended merely to represent the worst arrangements that could occur by chance. With 85 per cent average efficiency the joint arrangements could scarcely be considered to be poor.

$\bar{X}$ = Average Modulus of Rupture, p.s.i.

Conclusions

The experiment showed an efficiency of about 70 per cent for the unplaned feather-edged plain scarf jointed beams.

The presence of cross-grain may have confused the comparison somewhat but there is no clear evidence of any improvement in strength of the feather-edged plain joint as a result of planing.

None of the scarf arrangements planned to represent worst conditions were found to be bad. The efficiency of the special scarf arrangement groups averaged 85%.

Elma Kennedy.

APPENDIX B

Statistical Analysis

Definitions and Symbols:

average measurement or mean: $\bar{x} = (\Sigma x)/n$

where x = individual measurement

n = number of individual measurements

variance: $S^2 = \Sigma(x - \bar{x})^2/(n - 1)$

standard deviation: $S = \sqrt{\Sigma(x - \bar{x})^2/(n-1)}$

coefficient of variability: $V = S / \bar{x}$

pooled variance: $\sigma^2 = \dfrac{S_1^2(n_1-1) + S_2^2(n_2-1)}{(n_1-1) + (n_2-1)}$

standard error $= \sigma/\sqrt{N}$

where $N = n_1 + n_2$

degrees of freedom: D.f. = n-1

t-test

To determine the significance of the algebraic difference between two mean values ($\bar{x}_1$ and $\bar{x}_2$) the t-test has been used.

$$t = \bar{x}_1 - \bar{x}_2 / \text{standard error}$$

The probability value associated with this t value gives the probability by which a chance occurrence of the difference $\bar{x}_1 - \bar{x}_2$ may be expected. These calculated t-values are therefore compared with tabulated t-values to determine if the calculated difference is real or occurred by chance. Values of t are based on a normal distribution and are tabulated for various degrees of freedom and different probabilities (see "Standard Mathematical Tables", Chemical Rubber Publishing Company, 1955, Cleveland).

t - test

Initial Failures:

type of failure	beam type	D.f.	t calculated	t for 5% probability
tension	C	12	0.21	2.14
	S	2	1.94	2.31
	SP	6		
	C	12	2.72	2.10
	SP	6		
cross grain	C	4	5.9	2.15
	S	10	0.4	2.10
	SP	8		
	C	4	8.5	2.18
	SP	6		
failure at scarf	S	8	4.75	2.15
	SP	6		
group mean	C	17	5.34	2.04
	S	21	1.81	2.04
	SP	21		
	C	17	4.66	2.04
	SP	21		
scarf group mean	S	7	0.18	2.05
	S	21		
scarf group mean	SP	5	4.25	2.06
	SP	21		

t - test

Initial Failures:

type of failure	beam type	D.f.	t calculated	t for 5% probability
scarf group mean	S	7	5.81	2.06
scarf	C	12	0.033	2.07
	SP	5		

Ultimate Failures (group means):

beam type	D.f.	t calculated	t for 5% probability
C	18	5.68	2.03
S	18	2.71	2.02
SP	21		
C	18	3.88	2.02
SP	21		

Initial Failures: (group means, D.f. = 5 for each group)

beam type	t, calculated
X	0.45
Y	3.95
Z	2.44
CW	6.45
X	5.69
Z	
Y	5.18
CW	

Ultimate failures: (group means, D.f. = 5 for each group)

beam type	t, calculated
X	
	0.66
Y	
	0.31
Z	
	5.11
CW	
	6.38
X	
	2.36
Z	
Y	
	4.14
CW	

For D.f. = 10 and a 5% probability t = 2.23

APPENDIX C

UNIFORM GLULAM CERTIFICATE

LAMINATOR: Stein Roof Structures Ltd.

LAMINATING CONDITIONS AND PROCEDURES.

Date: January 17, 1957

Job Name: C.I.T.C. Test Beams Job Location: University.

1. LAMINATING MARK NUMBERS covered by this sheet include: S1 - 25 inclusive, C1 - 25 inclusive, SP1 - 25 inclusive.

2. LAMINATING STOCK species, grades, and assembly of grades into glulam members is in accordance with laminating specifications as per 0122-1953 for this job dated Jan. 17/57.

3. LAMINATING STOCK CONDITIONS

   (a) Moisture Content: Max. 10%, Min. 8%, Max. Var. per member 2%

   (b) Grade indentification by: D Clear - Outside lam selection.

   (c) Scarfs: Type Plain, Slope 1:12.

4. GLUE

   (a) Type: Casein (b) Manufacturer Monsanto (c) No. 1911

   (d) Manufacturer's Batch No. 256256. (e) Glue temperature at time of mix 60° F. (f) Mix: (by weight) Casein: 1-3/4 water to 1 dry glue.

5. MANUFACTURE

   (a) Assembly time: 40 minutes, 45 minutes.

   (b) Room conditions at time of gluing: D.B. 70°, W.B. 62°, R.H. 64%.

   (c) Glue spread: 90 lbs./MSFGL. (d) Clamp pressure: 100 plus/PSI.

6. CURING

   (a) Casein:

      1. Time under clamp pressure: 16 hours, 18 hours.

      2. Average room conditions during curing period:

         Dry bulb: 65°. Wet bulb: 58°. Rel. Hum. 66%.

[illegible] GLULAM CERTIFICATE

LAMINATOR: STEIN ROOF STRUCTURES LIMITED

LAMINATING CONDITIONS AND PROCEDURES

Date: March 2, 1957

Job No. B268
Job Name: CITC Test Beams Job Location: University.

1. MEMBER MARK NUMBERS covered by this sheet include: X1-6, Y1-6, Z1-6

2. LAMINATING STOCK species, grades, and assembly of grades into glulam members is in accordance with laminating specifications as per CSA-O122 for this job dated 1953.

3. LAMINATING STOCK CONDITIONS:

   (a) Moisture Content: Max. 10%, Min. 8%, Max. Var. per member 2%.

   (b) Grade identification by Density Selection.

   (c) Scarfs: Type- Plain, Slope 1:12.

4. GLUE:

   (a) Type: Casein (b) Manufacturer: Monsanto (c) No. 1911.

   (d) Manufacturer's Batch No. 255356. Glue temperature at time of mix: 70° (f) Mix (by weight)

   Casein: 1-?/4 water to 1 dry glue.

5. MANUFACTURE:

   (a) Assembly time: 30 min per clamping.

   (b) Room conditions at time of gluing: D.B. 70°, W.B. 62°, R.H. 64%.

   (c) Glue spread: 75 lbs./MSFGL. (d) Clamp pressure: 100 PSI.

6. CURING

   (a) Casein:

      1. Time under clamp pressure: 16 hrs.

      2. Average room conditions during curing period:

         Dry Bulb: 64° Wet Bulb: 56° Rel. Hum. 60%.

UNIFORM GLULAM CERTIFICATE

LAMINATOR: STEIN ROOF STRUCTURES LIMITED

LAMINATING CONDITIONS AND PROCEDURES

Job No. P268
Job Name: Test Beams Date: March 25, 1957

1. MEMBER MARK NUMBERS covered by this sheet include: Controls 1 to 7.

2. LAMINATING STOCK species, grades, and assembly of grades into glulam members is in accordance with laminating specifications as per CSA O122 for this job dated 1953.

3. LAMINATING STOCK CONDITIONS

   (a) Moisture Content: Max. 11%, Min. 8%, Max. Var. per member 2%.

   (b) Grade identification: by Density.

4. GLUE

   (a) Type: Casein (b) Manufacturer: Monsanto (c) No. 1911.

   (d) Manufacturer's Batch No. 256256 (e) Glue temperature at time of mix 68°. (f) Mix: (by weight) 1. Casein 1.75 water to 1 dry glue.

5. MANUFACTURE

   (a) Assembly time: 30 mins.

   (b) Room conditions at time of gluing: D.B. 68°, W. B. 61°, R.H. 67%.

   (c) Glue spread 80 lbs./MSFGL (d) Clamp pressure: 100 PSI.

6. CURING

   (a) Casein:

      1. Time under clamp pressure: 18 hrs.

      2. Average room conditions during curing period:

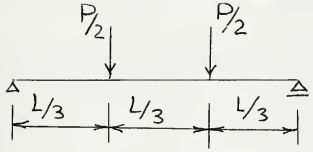
         Dry bulb: 66°, Wet Bulb: 60°, Rel. Hum: 70%.

APPENDIX D

Effect of Sliding Friction at the Supports on the Computation of the Modulus of Elasticity.

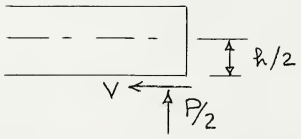
The modulus of elasticity of a material can be calculated from the deflections of a beam subjected to vertical loads. In making such a calculation it is usually assumed that the material is homogeneous, isotropic and obeys Hooke's law and that the deformations due to shear are negligible.

For a simply supported beam of uniform cross-section loaded at the third-points as shown the deflection will be:



$$\delta_1 = \frac{PL^3}{EI}\,\frac{23}{1296}$$

If only end-rotation but no free lateral movement of the ends is possible a thrust will be produced at the ends of the beam. Where the lateral restraint is caused by friction between the beam and its supports the magnitude of this thrust will be $V = \mu P/2$, where μ = coefficient of friction between wood beam and steel support.



This thrust will produce a bending moment

$$M = -Vh/2$$

$$= -\mu Ph/4$$

The deflection caused by this bending moment is:

$$\delta_2 = -(\mu PhL^2/32EI)$$

The total observed deflection therefore will be

$$\Delta = \delta_1 + \delta_2$$

$$= (PL^3/EI\cdot16)(23L/81 - \mu h/2)$$

and from this the modulus of elasticity can be calculated as

$$E = (PL^3/\Delta I\cdot16)(23/81 - \mu h/2L)$$

For the beams tested $h/L = 1/24.3$, while the coefficient of friction may be assumed as $\mu = 0.3$ to 0.5 .

With these values:

$$E = (PL^3/\Delta I\cdot16)(0.284 - 0.0102)$$

$$= (PL^3/\Delta I\cdot16)\ 0.274$$

This means that the actual modulus of elasticity is smaller by a ratio of $0.274/0.284$ than an E-value calculated without considering the thrust due to friction.

APPENDIX B

Some Remarks on the Structure of Coniferous Wood and the Nature of Failures in Such Wood Specimens

Douglas Fir belongs to the family of conifers or cone bearing trees. The wood of conifers is made up of small tubular cells, tracheids, which are formed in the cambium. (16). The cambium is the growing sheath between the wood and the bark. These tracheids (See Fig. 20 and 21) have a length of approximately 0.3 mm and a diameter of 0.003 mm (15). The tracheids occurring in the spring wood have relative thin walls, while those in the summerwood have thicker walls and are especially adapted for giving mechanical strength (16). (See Fig. 20). The cell walls are formed of cellulose, which is extremely strong in tension. Individual cells are bonded together by lignin. The longitudinal axis of the tracheids in general is parallel to the side of the tree.

Experiments show that the tensile strength of wood in the direction of the grain (tracheids) is larger than the compressive strength in the same direction (6). This is reflected in the respective design values for timber proposed in the National Building Code of Canada (12) and other codes (13, 4). Detailed investigation has shown that the tensile strength of the wood is derived from the tensile strength of the cell walls, while under compression the capacity is determined by the buckling strength of the tracheids (16).

Although the compressive strength is lower than the tensile strength, beams subjected to bending usually fail in tension (16). Bach and Baumann as early as 1924 (2) developed a flexural

theory that explains this phenomenon. Noting that the neutral axis is depressed below the centroid of the section with continued application of the load, they fitted the observed tension and compression stress-strain curves to the corresponding parts of the cross section (Fig. 15). The resulting stress-distribution over the cross section gives a higher stress on the tension side than on the compression side. If the tensile stress is large enough the beam will fail in tension.

In a direction perpendicular to the grain wood has little tensile strength. The compressive strength is also reduced in this direction, although not as drastically as the tensile strength. Considering the structure of the wood, the reason for the reduced strength becomes obvious. There are virtually no cellulose fibres extending in this direction and therefore little resistance to tension is offered in this direction.

The average maximum shear strength parallel to the grain is only a fraction of the maximum strength in compression (6). Again if we consider the tubular form of the tracheids, we see that the walls of these cells will be subjected to compressive as well as shear forces, which will cause failure at low loads.

One particular kind of failure in tension is caused by so-called cross grain. The term cross-grain includes all deviations of the grain from the direction of the longitudinal axis or longitudinal edges of the specimen (6). The principal types of cross-grain are diagonal grain and spiral grain (6). Diagonal grain results from sawing a piece of lumber at an angle other than parallel with the bark. The resulting "cross grain" can easily be identified by visual inspection.

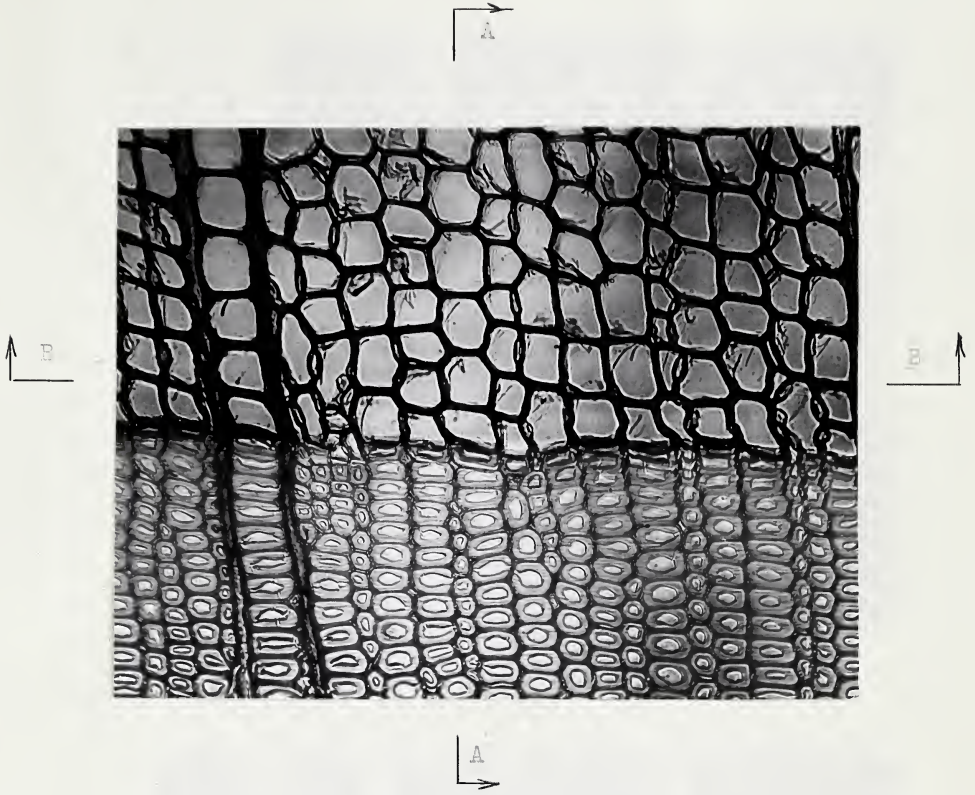
On the other hand spiral grain is difficult to detect (1). This latter type of cross grain is a structural characteristic that may be present in coniferous trees. Northcott (14) even goes so far as to say that spiral grain may be the normal pattern of growth in trees. However he does not make the claim that this has been proven definitely. Preston (15) gives the following definition of spiral grain:

"By the term spiral grain it is implied that the tracheids in the wood, instead of lying with their length parallel to the length of the trunk, are inclined to this length at a common angle, the grain therefore lying along a spiral around the trunk".

According to Preston (15) spiral growth is initiated in the growing cells of the cambium. In young trees spiral growth usually is left handed. After the inclination of the tracheids reaches a certain maximum the spiralling tendency stops and may even revert to a right-handed turn. Values of the inclination of the grain given by Preston (15) range from 2 to 13 degrees.

To visualize the mechanism of cross grain failure consider now a beam containing spiral grain subjected to bending moments. Principal stresses parallel to the longitudinal axis can be resolved into tensile and shear stresses on planes parallel to the direction of the grain. This means that there will be a tensile stress component acting across the grain. As has been pointed out earlier the wood can only resist little stress across the fibres. The specimen therefore will only be able to withstand a reduced flexural stress, the reduction depending on the slope of the spiral grain. Reduction factors for the modulus of rupture of wood members containing various

grain slopes as compared to straight-grained members have been published by the U. S. Forest Products Laboratory (6).

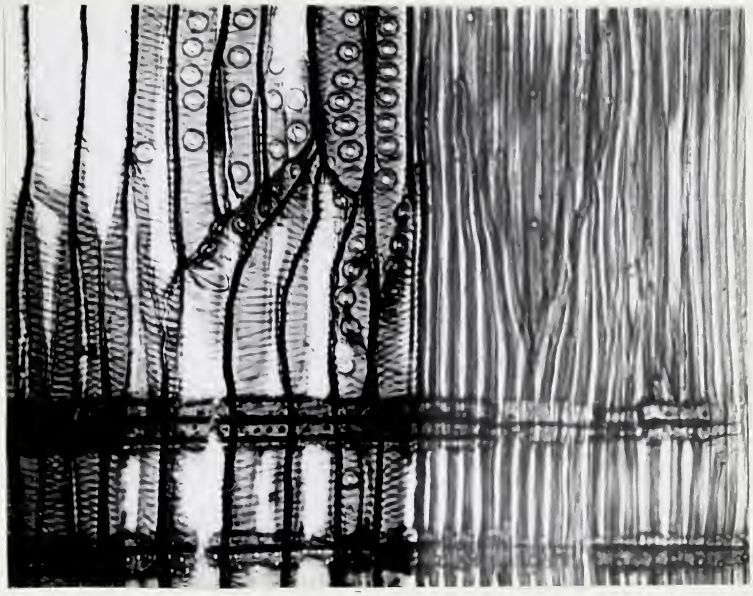


Cross Section of Douglas Fir (x120)

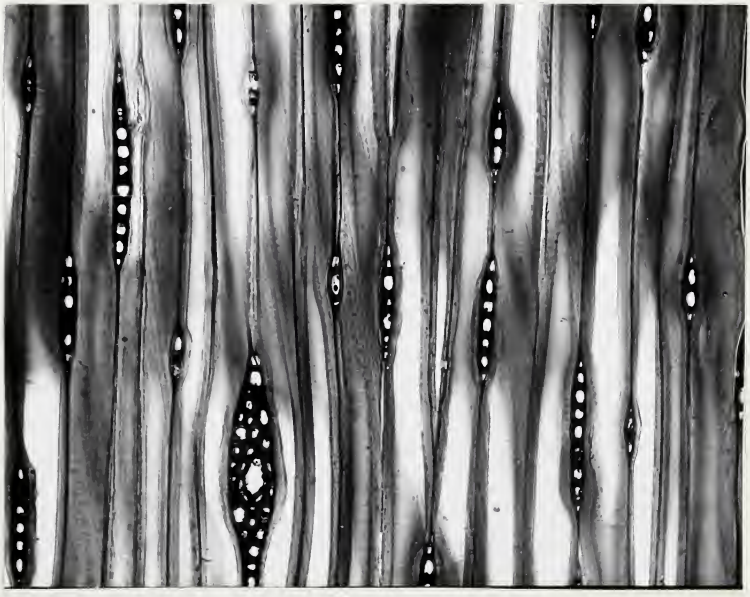
Top: Springwood

Bottom: Summerwood

Fig. 20



Longitudinal Section A - A (x120)



Longitudinal Section B - B (x120)

Fig. 21

B29777